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THE GEOLOGY OF THE MURRAY BASIN

by

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Melbourne, Australia
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ABSTRACT

This report gives an account of the petroleum geology of the Murray basin, having regard to the older rocks on the margins, and the sediments filling the basin. The Murray Basin is a large, shallow sedimentary basin in south-eastern Australia with an area of more than 100,000 square miles, occupying parts of the States of South Australia, New South Wales and Victoria. Its formation began probably in the Cretaceous period, and marine and estuarine sedimentation continued intermittently till late in the Tertiary. The margins and floor of the basin are composed of geosynclinal sediments of Proterozoic and Palaeozoic age, most of which have been strongly folded.

In this study of the basin reference was made to all relevant information, published and unpublished, which could be found, and a considerable amount of field work was done. The most important results are as follows.

It is concluded that there is little or no possibility of there being under the Murray Basin unmetamorphosed Cambrian sediments similar to the petroliferous rocks occurring further west in South Australia.

It was found that there is a much greater thickness of Upper Devonian-Lower Carboniferous sediments than was thought previously. A marginal trough developed in Upper Devonian times after the Taberabberan orogeny, in the middle of which more than 18,000 feet of sediments of flysch and molasse type accumulated. A fairly full account is given of the stratigraphy and structure of those sediments.

A review is given of what is known of the Cretaceous beds around the Murray Basin and from this evidence, and the little that is known of the Cretaceous in the basin, some conclusions are drawn about the possible extent and thickness of the Cretaceous in the basin.

A detailed study was made of the Tertiary outcrops along the lower reaches of the Murray River and this work, combined with borehole evidence, revealed a series of faults and monoclines along which movement was shown to have taken place at several times during the Tertiary.

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INTRODUCTION

This report gives an account of the petroleum geology of the Murray Basin and the older rocks on the margin of the basin. The Murray Basin is a large shallow structural basin which developed in the Cretaceous period, occupying parts of the States of South Australia, New South Wales and Victoria in southeastern Australia. It also forms a topographical basin, comprising a large area of about 100,000 square miles of dry sandy plains separated from the ocean to the east and south by the barrier of the Great Dividing Range which rises to heights of more than 6,000 feet. On the western side of the basin, between it and Gulf St. Vincent are the Mount Lofty Ranges, in which a Tertiary peneplain has been raised to a height of more than 2,000 feet. On the northern side of the basin there is a low divide on which older rocks crop out separating it from the similar, but much larger, Great Artesian Basin.

The heaviest rainfall is in the Dividing Range to the east and south of the basin, while the rainfall in the plains is much lower, decreasing in a northwesterly direction away from the mountains until in the Broken Hill area, in the northwest, the average annual rainfall is only about eight inches. Therefore the main rivers which cross the Murray Basin, the Murray, Murrumbidgee, Lachlan and Darling Rivers, rise in the mountains and flow across the plains in a westerly direction before turning south and entering the sea at the southwestern corner of the basin. In their course across the basin these rivers meander across wide flood plains which are frequently covered by flood waters in the winter. Further down the Murray River, however, below the town of Loxton, as a result of recent uplift, the river has cut a steep-sided gorge in which Tertiary limestones are well exposed.

Most of the sediments filling the basin are of Tertiary age deposited in a marine or estuarine environment in a gulf joined to the southern ocean by a channel in the southwestern corner of the basin. The greatest thickness of Tertiary sediments in the middle of the basin is less than 2,000 feet. Two boreholes in the middle of the basin have proved Cretaceous sediments underlying the Tertiary, but the extent of the Cretaceous beds is much less than that of the Tertiary. The surface of the basin is covered by a thin blanket of Quaternary alluvium and aeolian sand which covers the Tertiary rocks almost everywhere in the basin except along the banks of the lower part of the Murray River.

The floor and margins of the basin are formed by very thick sediments, ranging in age from Proterozoic to Carboniferous, deposited in a large geosyncline which occupied a large part of eastern Australia in the Palaeozoic era. Most of these sediments have been tightly folded and intruded by granites of several orogenies. There was no thick sedimentation in the Murray Basin area after the Middle Carboniferous Kanimblan orogeny. Probably the most severe of these orogenies in the area under discussion was the Middle Devonian Taberabberan orogeny with which many granitic intrusions were associated. After this orogeny, in the Upper Devonian and Lower Carboniferous, a thick series of sediments was deposited in a narrow trough and these sustained relatively mild deformation by later orogenies.

Previous Work

Previous geological work in this large area has been done mainly by the State and Commonwealth geological surveys with limited economic objectives, with the result that knowledge of the geology of the area is very patchy. For example the stratigraphy and structure of the Ordovician and Silurian rocks of the Victorian goldfields have been worked out in detail and there is a large amount of detailed information on the mineralised Archaean rocks of Broken Hill. The only part where regional mapping has been carried out to any extent without immediate economic objectives is in South Australia where geologists of the State survey have accumulated much information on the Proterozoic and Cambrian rocks in the last few years. On the other hand there are large areas and many groups of sediments which have received very little attention, usually because these areas or rocks contain no valuable mineral deposits. For example the Upper Devonian and Lower Carboniferous beds, although thick and having very extensive outcrops, have received little study beyond the reconnaissance level. In addition to those gaps in detailed knowledge, there has been also a shortage of attempts to fit together the considerable amount of information which is available in order to form a coherent picture of the larger structural units and sedimentary features. This shortcoming of Australian geological literature is probably due to some extent to the independence of the State geological surveys and the distance between their headquarters. A notable exception is the work of Professor Hills of Melbourne. Since such consideration of regional features and structural patterns is necessary to accomplish the objects of the present study, this report is to some extent breaking new ground.

Several appraisals of the oil possibilities of the Murray Basin have been made in the past by various oil companies, all being based on published work without any additional field work. These reports were unanimous in dismissing the oil prospects as poor because of the thinness of the Tertiary sediments and the presence in them of fresh water, and because of the alteration of, and granitic intrusions into, the Palaeozoic rocks. In the last few years two other companies have been working in the area, one in the basin, and one in the Cambrian rocks to the west. The Australian Oil and Gas Company has done some gravity work on the lower reaches of the Darling River in New South Wales and in 1956 drilled a well south of Loxton in South Australia which produced the interesting information that Cretaceous sediments underlie the Tertiary beds in the middle of the basin. The other company, Santos Ltd. followed up reports of oil shows in the Cambrian limestones of the southeast of Lake Torrens and drilled several wells which produced numerous small oil shows. However, the results were not encouraging and it is believed that Santos has lost interest in the area. The presence of oil in Cambrian rocks to the west of the Murray Basin is relevant, because the possibility has been mentioned of similar petroliferous Cambrian sediments being present under the Murray Basin.

Scope of the Survey

When the survey was begun in 1956, its main object was the study of the Palaeozoic rocks of the margin of the Murray Basin; it was intended that a study of the major features of sedimentation and structure would enable an estimate to be made of the possibility of unmetamorphosed and relatively gently folded Palaeozoic sediments being present under the Tertiary cover in the basin. With the discovery of Cretaceous rocks in the Loxton bore there was a change of emphasis and more attention was paid to the Mesozoic and Tertiary rocks.

possibility that petroliferous Cambrian sediments might underlie the Murray Basin. Although it is fairly brief this account is based on a study of all of the relevant literature that could be found. It involves the consideration of a wide area and also inevitably involves consideration of fundamental problems of geotectonics which might be thought rather theoretical for a report of this kind, but which cannot be avoided in any attempt to work out the distribution, thickness and facies of the Cambrian rocks underlying the later Palaeozoic rocks in eastern Australia.

Maps

A geological map of the Murray Basin and its margins on a scale of 1 inch = 16 miles (Plate 1) was compiled from maps from different sources, with varying scales and varying degrees of accuracy. The greatest amount of original mapping was done in New South Wales, and in the absence of suitable topographical maps the geology was plotted on uncontrolled photo-mosaics (Plates 2, 3, 4,) resulting inevitably in rather distorted maps. This more detailed work was incorporated in the 1 inch = 16 miles compilation, and in the absence of topographic control some distortion was involved in the fitting in of the various parts.

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ARCHAEOZOIC

Archaeozoic rocks appear east of a cover of Proterozoic and Cambrian sediments in the Broken Hill area, and further south in the cores of several large anticlines in the Mount Lofty Ranges. They do not crop out further east on the mainland of Australia but do crop out in Tasmania. The Archaeozoic rocks of the Broken Hill area, the Willyama Series, which contain one of the world's richest lead-zinc-silver ore bodies, are highly metamorphosed and were originally thin bedded argillaceous and arenaceous sediments. Regional metamorphism has converted these sediments over most of the area into sillimanite-biotite-garnet gneisses and sericite, andalusite and staurolite schists. In the extreme northern portion of the district the sediments are relatively little metamorphosed and somewhat resemble the overlying Proterozoic beds. Intruded into the Willyama Series are several stocks of granite, but there are no large batholiths. These metamorphosed sediments have been compressed into tight isoclinal folds which have a fairly uniform N.E.-S.W. axial direction. Two main sets of faults and shear zones cut the rocks. The first, the Mundi Mundi type, have a direction of $N20^{\circ}E$ to $N40^{\circ}E$ and are probably steep; the direction of movement is not known. The other set, the De Bavay type, has a direction of $N40^{\circ}W$ to $N10^{\circ}W$, a very steep dip to the northeast and a sinistral displacement. There is also a large east-west 'crush zone', the Thackeringa crush zone, which appears to be basically a buckle with fold axes on both sides pitching downwards towards it.

The Archaeozoic inliers of the Mount Lofty Ranges are composed of rocks similar in composition and degree of metamorphism to those of the Willyama Series.

PROTEROZOIC

Rocks of the Upper Proterozoic Adelaide System have a very extensive outcrop on the western and northwestern side of the Murray Basin. The Adelaide System is a series of sediments with a maximum thickness of more than 40,000 feet deposited in the Adelaide Geosyncline, which developed in the Proterozoic era on the eastern side of the Australian Shield. The details of the sedimentary divisions are given in Table I.

The lower two divisions, the Willouran and Torrensian Series, crop out in the west and northwest where the Adelaidean sediments dip outwards off the shield. In the northeast, where the Archaeozoic basement reappears at the surface in the cores of folds and in the large area at Broken Hill, the Sturtian Series is thought to rest directly on it and the lower two divisions are thought to be missing. However at one place north of Broken Hill the glacial Sturtian sediments are separated from the Archaeozoic by basalts 'underlain by thin bands of limestone, sandstone and grit, which unconformably overlie Willyama schists' (King and Thomson, 1953, p.547). The writer has also seen basalt interbedded with the Adelaidean sediments at several places east of Broken Hill. Since basalts in the northwestern part of the Adelaidean outcrop are thought to be of late Torrensian age, it is possible that Torrensian sediments may not be completely absent from the Adelaide System in the Broken Hill area, as is usually claimed.

TABLE 1

ADELAIDE SYSTEM IN SOUTH AUSTRALIA

AFTER GEOLOGICAL MAP OF SOUTH AUSTRALIA
PUBLISHED BY THE GEOLOGICAL SURVEY OF SOUTH AUSTRALIA 1953

Division	Maximum recorded thickness(feet)	Lithology
Marinoan Series	11,300	Reddish chocolate and grey slates, limestones sandstones and quartzites frequently with macigno (sandstone-shale) associations and brecciolic limestones indicating submarine slopes. Restricted arkoses and the Elatina tillite of Flinders Ranges. Problematic Cryptozoa.
Sturtian Series	24,450	Massive tillites, glacigenes and laminated slates. Macigno (sandstone-shale) associations and limestone brecciolas including red "hieroglyphic" limestones near top; iron formations in Olary province.
Torrensian Series	17,000	Massive well sorted (basal) sandstones attaining 6,000 feet in thickness, with or without massive conglomerates in westerly geosynclinal and shelf zones. Grey shales with interbedded thin limestones and brecciolic sedimentary magnesites and quartzites.
Willouran Series	3,000	Occurs at the base of the Adelaide System only along the western margin of the geosyncline. Numerous quartzites interbedded with fine argillaceous shales.
Kalabity Series		Possibly metamorphosed Sturtian Series. Occurs only in the Olary province. Quartzites and various schists principal amongst which is chiasolite schist. Garnet-epidote rock.

It does appear certain, however, that there was a period of uplift and erosion before the Sturtian glaciation, during which most of the pre-Sturtian sediment was stripped from the Broken Hill area, and probably the whole of the geosynclinal area to the west was also subjected to sub-aerial erosion.

The dominantly red sediments of the Marinoan Series at the top of the Adelaide System are preserved in synclinal areas only in the northwest and in a few small patches in the Mount Lofty Ranges. However the writer found a small patch of sediments near the Cootawundy Hills (Plates 2 and 3) east of Broken Hill, which might be of Marinoan age and, although only a very brief examination was made of the area, the results are worth putting on record. There is a broad N.W.-S.E. shear zone on the western side of Koonenberry Mountain and in it the green calcareous mudstones of the Sturtian Series are converted to schists and mineralised. At the southeastern end of this zone the sheared Sturtian sediments are overlain by an unmetamorphosed, relatively gently folded series of white sandstones and soft red mudstones which are overlain by horizontal Upper Devonian sandstones. The red mudstones and white sandstones might belong to the Marinoan Series. On the other hand it appears that most of the shearing which produced the schistosity in the Sturtian sediments preceded the deposition of the white sandstones, and no major earth movements are known between Sturtian and Marinoan times. Therefore a correlation with the red beds at the top of the Cambrian is possible, as Daily (1956) has described fairly strong earth movements in the Lower Cambrian. However for the present these beds are not separated from the surrounding Adelaidean sediments on the evidence of the one brief examination.

Igneous Rocks

In addition to the interbedded basalts cropping out in the Broken Hill region the Adelaidean sediments also contain numerous small bodies of pink and pale red rhyolite and porphyry. Most of them are concentrated along the Koonenberry shear zone in a way suggestive of some structural control of their distribution. Some are definitely intrusive but some may be interbedded lavas. For example the porphyries to the west and southwest of the Cootawundy Hills (Plate 3) give the impression of following the one stratigraphic horizon not far below the base of the white sandstones and red mudstones of doubtful age described above. It has been suggested that these porphyries might be 'epi-Devonian', but the abundance of the porphyries in the Adelaidean sediments along the Koonenberry shear zone and their absence in the extensive, well-exposed Upper Devonian beds makes it certain that they are older than the Upper Devonian.

A continuation of the porphyries to the south into the Murray Basin was proved in a borehole southeast of Menindee which revealed 60 feet of porphyry underlying Cretaceous and overlying slate (see Plate 7). A further continuation into the central part of the basin is suggested by geophysical work. A small circular geophysical 'high' west of Mildura coincides with a magnetic 'high' suggesting an intrusive mass of igneous rock, which is shown by the relatively low gradients to be in the basement and not in the Tertiary. This postulated igneous intrusion is therefore pre-Tertiary and could be either a mass of porphyry, of the same age as those in the Koonenberry area to the north, a Cambrian granite, like those to the south and southwest, or a Kanimblan (Middle Carboniferous) granite like the stocks in the Upper Devonian sandstones of the Grampian Range to the southeast.

Structure and Metamorphism

Most of the folding of the Adelaidean sediments, with its related granitic intrusion and metamorphism, took place at the same time as that of the Cambrian beds and a detailed description of the tectonics will be given in the next section.

CAMBRIAN

There are extensive Cambrian outcrops on the western side of the Murray Basin in South Australia where Cambrian sediments followed the Proterozoic conformably. On the eastern and southeastern sides of the basin, in New South Wales and Victoria, there are only a few small outcrops. These have complex structure and have yielded fossils only at a few localities in Victoria. A very good summary of all that is known about the Cambrian of Australia was published recently by the International Geological Congress in 1956 and the present account relies to a large extent on that publication.

The object of this survey, the study of the pre-Tertiary rocks around the Murray Basin and the deduction from this study of the changes to be expected in the rocks under the Tertiary cover, is a difficult one in the case of the Cambrian. The sedimentary succession on the western side of the basin is well exposed and well understood, but the outcrops on the eastern side are of very different sediments. Any attempt to deduce the lithology and thickness of the Cambrian rocks in the intervening areas, including the Murray Basin, involves inevitably a consideration of evidence from a wide area and of different kinds, and involves also the fundamental geotectonic question of the nature of the edge of the continent. A full discussion of these subjects is beyond the scope of this paper, but a brief account of the main conclusions and an outline of the evidence that led to them will be given.

SOUTH AUSTRALIA

A stratigraphic table of the Cambrian rocks of South Australia is given in Table 2 which shows the succession in the northern part of the Adelaide Geosyncline near Lake Frome, where there is a thickness of over 17,000 feet, and that of the Kangaroo Island region in the south where the thickness is only 5,500 feet. The Cambrian sediments followed the Proterozoic conformably and the base of the Cambrian is taken arbitrarily at the base of a distinctive sandstone with a wide extent, the Pound Sandstone. The Cambrian sediments, with the exception of the Kanmantoo group of the southeast, are normal marine, continental shelf deposits consisting of well sorted sandstone, shales and limestones which in some places are composed of reefs of Archaeocyathina. The limestones have provided numerous small shows of oil and bitumen but no larger amounts have been found in the recent exploratory drilling. Daily (1956) has worked out a series of faunal assemblages, mainly trilobites, in the South Australian sediments which range in age up to the Redlichia Zone in the lower part of the Middle Cambrian. There are no sediments younger than the Redlichia Zone in the Adelaide Geosyncline, in which deposition is thought to have been closed by an orogeny in the succeeding Gibbus and Dinesus Zones in the middle part of the Middle Cambrian.

	SUCCESSION OF FAUNAS	LAKE FROME AREA 17,250	KANGAROO IS. REGION 5,500 +	EASTERN MT. LOFTY RAS.
MIDDLE CAMBRIAN		LAKE FROME GROUP		
		GRINDSTONE RANGE <i>Sandstone</i> 1,400		
		<i>Sandstone</i> 4,500		
		BALCORACANA Formation 1,500		
		MOODLATANA Formation 1,300		
	ASSEMBLAGE 10	WIRREALPA <i>Limestone</i> 350		
		BILLY CREEK Formation 3,300	BOXING BAY <i>Sandstone</i> 2,500 +	
	ASSEMBLAGE 9	ORAPARINNA <i>Shale</i> 700	EMU BAY <i>Shale</i> 350	
		BUNKERS <i>Sandstone</i> 700		
	ASSEMBLAGE 8	PARARA <i>Limestone</i> 2,000	WHITE POINT <i>Conglomerate</i> 1,250	KANMANTOO GROUP
LOWER CAMBRIAN	ASSEMBLAGE 7			
	ASSEMBLAGE 6			
	ASSEMBLAGE 5			
	ASSEMBLAGE 4		CLASTICS 450	
	ASSEMBLAGE 3			
	ASSEMBLAGE 2			
	ASSEMBLAGE 1	WILKAWILLINA <i>Limestone</i> 750	?	
		POUND <i>Sandstone</i> 750	STOKES BAY <i>Sandstone</i> 1,000	
PRE-CAMBRIAN		MARINOAN SERIES OF ADELAIDE SYSTEM UPPER PROTEROZOIC	<i>Phyllites - quartzites of ADELAIDE SYSTEM</i>	

Note: Thicknesses in feet.

TABLE 2

CAMBRIAN CORRELATION OF SOUTH AUSTRALIA

(After B.DAILY, 1956)

Fairly strong orogenic movements in Lower Cambrian times in the southeastern part of the geosyncline have been suggested by Daily. A thick conglomerate, the White Point Conglomerate, contains boulders with a fauna from Assemblage 2 and is overlain conformably by sediments with a Lower Cambrian fauna, showing that the movements took place in Lower Cambrian times later than Assemblage 2. The evidence of this Lower Cambrian orogenic movement suggests a solution for the long-standing problem of the age of the Kanmantoo Group. This is a group of unfossiliferous, metamorphosed sediments with intrusive granites which crop out along the eastern side of the Mount Lofty Ranges and disappear eastwards under the Tertiary cover of the Murray Basin. They are usually thought to be Cambrian in age, but are different in facies, being of greywacke or flysch type in contrast with the stable shelf deposits of the rest of South Australia. Daily thinks that the Kanmantoo Group is a lateral equivalent of his Kangaroo Island Group and that its sediments were derived from a cordillera formed by the Lower Cambrian orogenic movements.

Structure

Deposition in the Adelaide Geosyncline was closed by strong orogenic compression, probably in the Middle Cambrian, which formed a belt of folded Adelaidean and Cambrian sediments with a sigmoidal form, east-northeast in the north, turning to a north-south direction in the middle, and turning again to an east-west direction in the south. In this orogenic belt there is a gradual westerly decrease in the intensity of the folding, and the thin sediments which lap over the Australian Shield west of Lake Torrens are here unfolded. In the eastern part of the orogenic belt, the Mount Lofty-Olary Arc, there are axial culminations in the Mount Lofty area in the south and in the Olary area in the north, where anticlinoria bring Archaeozoic rocks to the surface in the cores of the folds. The anticlinoria are characterized by sharply overturned anticlinal folds separated by broad, intensely corrugated synclinal troughs. The reversed limbs of the anticlinal cores are strongly attenuated and they grade laterally into thrusts dipping at angles as low as 15° . Campana (1955) has interpreted the structure as caused by a plastic mantle of Adelaidean sediments adjusting themselves to an Archaeozoic basement which has been folded and thrust westward in slices. Thus the lower parts of the sedimentary cover are overfolded and thrust while the structures are much gentler in the higher beds. This decrease in intensity of folding in the younger sediments can be seen in the anticlinoria and the decrease can also be traced laterally into the area between the culminations where the folds are not so steep and there is no thrusting.

To the northeast of the Olary area in South Australia, where the Broken Hill massif brings Archaeozoic rocks to the surface, there is a very sharp turn, almost a right angle, in the direction of fold axes in the Adelaidean. This phenomenon has received almost no mention, probably because the change in direction coincides approximately with the State boundary. The sharpness in the change of direction is shown by the Adelaidean outcrops near Broken Hill. Less than 30 miles to the south of the city, Proterozoic sediments are in folds with east-west axes (B.P. Thomson, in an unpublished report) while 20 miles northeast of the city is the nearest part of extensive outcrops of Adelaidean sediments in folds with north-south to N.N.W.-S.S.E. axes. No explanation of this change in fold direction has yet been offered.

Similar at Hawkes Bay
(Central area)
Broken Syncline

In contrast to the Mount Lofty-Orary arc, where folding was the dominant form of deformation, and faulting of secondary importance, there are some major fault zones in the Broken Hill massif, fault zones which might, in fact, form the boundaries of the massif. The Koonenberry shear zone, near the eastern limit of the Adelaidean outcrop, has a N.W.-S.E. direction. Along it, for a width of several miles the Adelaidean shales and mudstones are highly sheared and are schistose in the zones of most intense shearing. In the shear zone there is mineralisation with copper, gold, lead and zinc. The consistent vertical attitude of the sheared beds shows that the zone as a whole is approximately vertical. Later movements affecting the Upper Devonian sandstones have been interpreted as a sinistral horizontal displacement and it is possible that the movements which caused the shearing in the Adelaidean sediments were of the same kind. There is evidence of a southerly continuation of this important fault line into the Murray Basin in the Upper Devonian rocks and it seems very probable that its effects will be strong on any Cambrian beds in the basin.

The second major fault line is the Redan Fault, a N.N.W.-S.S.E. fault on the southern side of the Broken Hill Archaeozoic outcrop. Exposures are poor and the evidence is mainly geophysical, but it does appear to be a fault of major importance which might form the southern boundary of the Broken Hill massif.

Granite intrusions and metamorphism

In the southern part of the orogenic belt in Kangaroo Island, and on the eastern side of the Mount Lofty Ranges the Adelaidean and Cambrian (Kamantoo) sediments have been intruded by granites and subjected to regional metamorphism. The metamorphosed Kamantoo sediments are covered to the east by Tertiary sediments but they reappear together with intrusive granites along the valley of the Murray River. Further east there are numerous small inliers of granite on the Padthaway Ridge, an uplifted ridge over which the Tertiary beds are thinner. Recent work seems to show that these granites are of the same age as those in the Kamantoo rocks of the Mount Lofty Ranges (Mawson and Parkin, 1943 and Mawson and Dallwitz, 1944) and if this is so it would prove that any Cambrian sediments in this area must be metamorphosed to some extent.

In the Broken Hill area the Adelaidean sediments are not metamorphosed, except along the Koonenberry shear zone, and are only slightly cleaved. Some small masses of granite which appear in the Adelaidean outcrop used to be thought of as intrusive into the Adelaidean, but there is now some doubt, and it is probable that they are pre-Adelaidean granites. At the northern limit of the known part of the Adelaide geosyncline there are granite intrusions to the northwest of Lake Frome which have metamorphosed Adelaidean sediments.

In the western part of the orogenic belt, near the Australian Shield, the folding is gentler and there is no metamorphism or cleavage. It was in this area of gentle folds southeast of Lake Torrens that most of the oil shows in the Cambrian limestone were found.

VICTORIA

In Victoria, Cambrian rocks crop out from below later Palaeozoic rocks only in several narrow belts of complex structure, the nature of which is not yet fully understood. The base of the Cambrian beds does not crop out and therefore the total thickness which is present in Victoria is not known. Fossils have been found at only a few outcrops; correlation with the Cambrian at

No precise boundary to the survey was set, the only criterion in deciding the limits being the relevance of any outcrops to the problem of elucidating the sedimentation and structure. Thus reference is made to some areas distant from the Murray Basin in the process of fitting the Murray Basin area into the sedimentary and structural pattern of any period.

Almost two years, from September, 1956 to July, 1958 were spent on the project - on field work, the studying of literature, the preparation of maps, and the writing of the report. Also two interim reports were prepared, one on the Victorian part of the basin, and the other a brief summary of results after the field work was completed and before the maps had been prepared. The field work was carried out by the writer alone, except for two months in 1956 when a field assistant was employed.

While rocks of all ages from Archaean to Quaternary were studied to some extent, attention was concentrated on those rocks which were considered to have the best oil prospects. Those rocks which were considered, as a result of early work, to have little chance of containing oil, for reasons of thickness or degree of alteration, received little attention in the field and are described only briefly in this report. Another important factor in the allocation of time to the various groups of rocks was the amount of previous work; these groups which had received little attention in the past needed more investigation in the field.

By far the greatest amount of field work was devoted to the Upper Devonian-Lower Carboniferous sediments because they are a better petroleum prospect than the older Palaeozoic rocks and because so little was known about them previously. It is on the subject of these rocks that the greatest additions were made to knowledge of the geology of the area. It was found that more than 20,000 feet of sediments were deposited in the marginal trough formed after the Taberabberan orogeny. A study of the stratigraphy and structure enabled some deductions to be made about the extent, thickness, facies and structure of those beds to be expected under the Murray Basin. A fairly detailed account of the work is put on record in this report.

The Tertiary sediments in the basin were also studied in some detail although it is fairly certain that the chances of economic accumulation of petroleum in them is negligible. This was done because the working out of the structure of the Tertiary sediments, the pattern of faults and monoclines, is very useful in the problem of estimating the extent and structure of the Cretaceous sediments which are known to underlie the Tertiary in the middle of the basin. Another benefit to be expected is that the working out of the stratigraphy in this shallow basin will help in the understanding of the stratigraphy of the thick sediments in the Gambier Sunkland in the south, particularly the horizons at which unconformities are to be expected and the periods at which faulting and uplift took place. The cliffs of Tertiary sediments along the lower part of the Murray River were studied and an analysis of all the available borehole information was made. The results are plotted on a structural map (Plate 7) which is the first attempt, as far as the writer knows, to present such a map of the Murray Basin as a whole.

An account is given of the Cambrian rocks of south-eastern Australia in an attempt to deal with the question of the

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the others has been based on lithological similarity. The best section was measured along the Heathcote-Colbinabbie belt, east of Bendigo (Thomas and Singleton, 1956) and is given in Table 3.

TABLE 3

<u>Age</u>	<u>Thickness</u>	<u>Division</u>
? Middle-Upper Cambrian	2,000 feet	Goldie Shales
Middle Cambrian	500 feet	Knowsley East Formation
Lower - ? Middle Cambrian	5,000+feet	Heathcote Greenstones

The only sediments which have been dated by fossils are some richly fossiliferous beds in the Knowsley East Formation which have a Middle Cambrian fauna. These pass downwards by gradation into the greenstones, the Lower Cambrian age of which is not confirmed by palaeontological evidence. Similarly the Goldie Shales are unfossiliferous and there is no palaeontological confirmation of the Upper Cambrian dating.

The Heathcote Greenstones are altered basic to intermediate lavas, pyroclastics, minor intrusives and lenticular cherts containing Protospongia and radiolaria. The lavas are considered to be partly, if not wholly submarine. There is gradual transition upwards to the Knowsley East Group which consist of interbedded cherts, black shales and thin ash beds. The overlying Goldie Shales are an unfossiliferous series of black shales and mudstones, silicified in outcrop, in which there are no ash beds. These are followed, apparently conformably by the Ordovician, the boundary being taken at the entry of the first greywacke. The outstanding feature of the Cambrian beds of Victoria is the absence of all but the finest terrigenous sediment. It is clear that the source of the sediment was distant or was separated from the area of deposition in Victoria by some barrier. On the other hand the sediments were not abyssal, as the trilobite and brachiopod faunas of the Middle Cambrian show.

NEW SOUTH WALES AND QUEENSLAND

There are several small outcrops in New South Wales and Queensland of fine grained sediments and basic lavas similar to those in Victoria, which underlie the Ordovician beds and which are probably of Cambrian age, although there has been no palaeontological confirmation of this correlation.

TASMANIA

In Tasmania there is a thick series of coarse grained post-orogenic sediments overlying the Proterozoic which are all of Middle and Upper Cambrian age (the Dundas Group) and which are thought to have been derived from mountains formed by the Middle Devonian orogeny which put an end to sedimentation in the Adelaide geosyncline.

Cambrian

PALAEOGEOGRAPHY AND TECTONICS

The palaeogeography and regional tectonics of the Cambrian System must be considered in any attempt to estimate the distribution, thickness and lithology of the Cambrian sediments under the cover of younger rocks in eastern Australia and in particular under the Murray Basin. Consideration of these subjects of tectonics and palaeogeography raises a question of fundamental importance in the geotectonics of eastern Australia, the question of the nature of the eastern side of the Adelaide Geosyncline. In no published work, as far as the writer knows, has this question been squarely faced. In any discussion of Proterozoic or Cambrian tectonics or palaeogeography it either receives only a passing reference or else is completely ignored. The usual assumption is that there was a rigid hinterland on the eastern side of the geosyncline, following the classical Alpine and Caledonian pattern, and most palaeogeographic maps show eastern Australia as a land area in the Cambrian, with a 'gulf' to accommodate the Victorian outcrops. This assumption would raise the possibility that gently folded platform sediments, like those of the western side of the geosyncline on which oil has been found, might be present on the eastern side of the geosyncline and that remnants of these sediments might be present under the Murray Basin, with obvious implications relating to the possibility of oil being found in the basin. For example Campana (1955), in his paper on the Mt. Lofty-Otway arc, shows on his structural map a 'hinterland' on the eastern side of the Adelaide geosyncline coinciding in area with the Murray Basin.

If the term 'hinterland' or 'craton' used for the eastern side of the geosyncline, is intended to have the meaning of a raised, rigid block, resistant to later orogenesis, then the hypothesis is contradicted by the evidence of Cambrian sedimentation and subsequent structural development. There seems to be little doubt that an uplifted belt did exist on the eastern side of the geosyncline. Recently Opik (1956) presented an interpretation of this eastern margin which appears to be more in accord with the evidence. He shows on his palaeogeographic map of the lower part of the Middle Cambrian a 'meridional divide', a narrow belt of land extending along the eastern side of the Cambrian geosyncline and separating it from the ocean to the east. In northern Australia it was a low divide which formed a faunal barrier and in the southern part of Australia, Opik thinks that, although it was higher, 'a foreland character is not evident' (Opik, 1956, p.277).

The Broken Hill massif, which is on this 'divide', was certainly a relatively rigid block, on which the Proterozoic sediments become thinner and on which they have received little or no granite intrusion or metamorphism. However there is no evidence for a southward continuation of this massif and the Redan Fault, at the southern side of the present Arohaean block, may have been approximately on the southern boundary of the massif in Proterozoic and Cambrian times.

The sediments throughout eastern Australia, extending almost as far west as the Victoria-South Australia border, show no signs of a nearby land mass, consisting of lavas, cherts and fine marls and silts. The presence of only the finest of terrigenous sediments in Victoria suggests that a continuation of the 'meridional divide' might have cut off this area from the main sources of sediment on the Australian Shield.

The later orogenic history of the eastern side of the Adelaide Geosyncline south of the Broken Hill massif shows that it did not act as a stable block. The granite outcrops on the Padthaway Ridge in South Australia, which are thought to be Cambrian, link up with metamorphic rocks in western Victoria which are thought to be

Ordovician and which have been intruded by granite. Whatever the precise age of all these granites it appears that the whole of the eastern side of the Adelaide Geosyncline along this east-west line parallel to the present coast, has been involved in Palaeozoic orogenesis and granitic intrusion. The northward continuation of this belt for a considerable distance into the Murray Basin was shown by the Shaugh Bore (see Plate 7) which encountered schist under the Tertiary. It appears, therefore, that south of the Broken Hill massif the eastern side of the Adelaide geosyncline was a mobile area in the Palaeozoic orogenies in the course of which it received many granite intrusions. This type of uplifted area on the eastern side of the geosyncline seems to be similar in most features with the Benambran geanticline that rose in eastern Australia in the orogeny at the end of the Ordovician. If these two uplifted belts are accepted as being of a similar nature, then it follows that the tectonic history of the Adelaide Geosyncline should be regarded only as an earlier chapter in the history of the Tasman Geosyncline, an earlier chapter in which the main tectonic features were not radically different from those during the life of the Tasman Geosyncline.

From the evidence which has been given and the interpretation of regional tectonics based on it, it follows that there cannot be under the Murray Basin an area of gently deformed Cambrian sediments similar to those on the western side of the Adelaide Geosyncline.

ORDOVICIAN

Rocks of Ordovician age crop out intermittently along a large part of the southern and southeastern margins of the Murray Basin extending from a short distance east of the South Australia-Victoria border eastwards through Victoria, and northwards into New South Wales, ending about the line of the Lachlan River. No rocks of Ordovician age have been found throughout the rest of the basin margins to the west and northwest in South Australia and western New South Wales. The nearest Ordovician outcrops in that direction are in the Amadeus Basin in the far north of South Australia. A great deal of detailed work, including the working out of graptolite zones, has been done on the Ordovician beds in Victoria, mainly because they contain the richest gold mineralisation in Victoria, notably at the rich Ballarat and Bendigo goldfields. Very little is known of the stratigraphic succession, structure and fossil content in New South Wales.

The table given below shows the variations in thickness of the various divisions at several localities in central Victoria.

TABLE 4

Ordovician rocks of central Victoria
From Hills and Thomas (1953)

Thicknesses are in feet

	<u>Chewton Area</u>	<u>Bendigo Area</u>	<u>Ballarat Area</u>	<u>Mornington Area</u>	<u>Lancefield Area</u>
U. Ordovician	-	-	-	1000+	2500
M. Ordovician	-	1500	-	500	1000+
{ Yapeenian	-	1200	-	?	1100
{ Castelmianian	1300+	1500	-	800	600
L. Ord. { Chewtonian	1150	2000	-	450	600
{ Bendigonian	500+	2030	-	600	1200
{ Lancefieldian	-	1200+	10000	1500+	5000

The Ordovician rocks, which appear to rest conformably on the Cambrian in the region of the Heathcote-Colbinabbin belt, are a remarkably uniform series of geosynclinal greywackes and black shales with a total thickness of 10,000-15,000 feet. A characteristic feature throughout the succession is graded bedding, with grading from greywacke at the base of the unit upwards to shale which has usually been altered to slate. This graded bedding, and the flow folding commonly associated with it, has been interpreted by Hills and Thomas (1953) to be the result of submarine turbidity currents caused by large scale slumping of unconsolidated sediments.

At all the outcrops in Victoria the Ordovician sediments are of the graptolitic, greywacke facies described above; there is no sign anywhere of a neritic facies or even of approach to a land mass in the belt of outcrops 250 miles wide in Victoria. The sediments were laid down in a wide geosyncline which subsided uniformly from the end of the Cambrian period throughout the whole of the Ordovician. Shelf sediments on the western margin of the geosyncline have all been removed by erosion and all that are left are the highly folded geosynclinal sediments. The western margin of the geosyncline was probably about the position of the South Australia-Victoria border. The earliest clear evidence of the existence of this geosyncline, the Tasman Geosyncline, is in the Ordovician sediments. The broad geosyncline stretched without interruption in a north-south direction along the whole length of eastern Australia.

The Ordovician sediments in Victoria and New South Wales have been strongly folded and a slaty cleavage has been imposed on the argillaceous rocks in most places. The axes of the folds have a north-northwest direction parallel to the length of the geosyncline. The usual kind of folds is of the chevron type with straight, steep limbs and sharp crests. In central Victoria, where the structure is well known, the folded sediments are cut by numerous reverse faults parallel to the fold axes, with steep dips to the east.

The Ordovician rocks have been intruded by numerous granite batholiths throughout the whole of their outcrop from eastern Victoria as far west as the most westerly outcrop near the South Australian border. Around the granite intrusions are broad zones of metamorphism. Beyond the metamorphic zones the sediments contain numerous quartz reefs which in many places have rich gold mineralisation. Most of the granites in the Ordovician sediments around the Murray Basin were probably emplaced in two main orogenies; the Benambran at the end of the Ordovician or in the early Silurian and the Taberabberan in the Middle Devonian. In many places it is impossible at present to differentiate between granites of these two ages.

A northward continuation of the cleaved Ordovician sediments with intrusive granites into the eastern part of the Murray Basin is indicated by several boreholes around Lake Tyrrell and by a small inlier of granite further east. It seems certain that any Ordovician rocks in the deeper parts of the Murray Basin along the strike of the geosyncline from the Victorian outcrops will not have been subjected to appreciably less intense deformation or granitic intrusion.

SILURIAN - MIDDLE DEVONIAN

The Silurian rocks have a wide outcrop extending intermittently from central Victoria, east of the Heathcote-Colbinabbin belt, round the southeastern corner of the Murray Basin into New South Wales, and northwards along the eastern margin of the basin as far as the line of the Darling River where the Silurian rocks disappear under the Mesozoic sediments of the Great Artesian Basin. Throughout the whole of this area there was probably a conformable passage from Silurian to Lower Devonian beds, which makes it more convenient to discuss the two divisions together.

In the early part of the Silurian Period there was an orogenic epoch, the Benambran Orogeny, which caused a geanticline of folded Silurian beds to rise in eastern Australia extending in a roughly north-south direction parallel to the axis of the geosyncline. On this geanticline Upper Silurian rocks rest with strong unconformity on the Ordovician. To the west there was continuous deposition from the Ordovician to the Silurian in a reduced geosyncline. The influence of the Benambran Orogeny was reflected in the increased rate of sedimentation and in the change in the type of sediment from that of the Ordovician period. The sediment was coarser and a green colour predominates in the argillaceous sediment in contrast with the black shales of the Ordovician. In Victoria there are numerous lenticular beds of conglomerate which are thought to be slump breccias (Hills and Thomas, 1954). A graptolitic fauna predominates in the lower part but gradually gives way in the higher beds to a shelly fauna.

A section measured on the eastern side of the Heathcote-Colbinabbin belt in central Victoria (Thomas, 1957) is given below.

TABLE 5

Age	Division	Thickness in feet	Lithology
Yeringian (Lower Devonian)	Mt. Ida Beds	7,000	Sandstones and grits
Silurian-Devonian	McIvor Beds	5,000	Sandstones
Lower Ludlow	Dargile Beds	5,000	Mudstones with one thick bed of sand- stone.
	Wapentake Beds	5,000	Lower part of mud- stone, upper of sandstone.
	Costerfield Beds Base not seen	2,000	Mudstones with thin sandstones
	Total	24,000	

The Dargile Beds have a graptolite fauna of Lower Ludlow age and the Mt. Ida Beds have a Yeringian (Lower Devonian) shelly fauna. The intervening McIvor Beds, which have a rich shelly fauna, must include the Upper Ludlow sediments, as the succession appears to be conformable, and perhaps also some sediments of Lower Devonian age, but the decision on the position of the Silurian-Devonian boundary awaits detailed work on the faunas.

The western limit of the Silurian outcrop in Victoria is the Heathcote-Colbinabbin belt of faulting and, as in the case of the Ordovician, the sediments of neritic facies in the west have all been removed, making it impossible to define precisely the western limit of the deposition. The western limit of the thick geosynclinal deposition was probably somewhere in the western half of Victoria.

The sediments in the Cobar area are similar, in general, to those in central Victoria, but the stronger influence of the Benambran orogeny is shown by the thick boulder conglomerate at the base. There are also some cherts. As in central Victoria the upper part of the conformable succession is probably of Lower Devonian age. Further south, there is an interesting outcrop around Mt. Squarehead near Narrandera, in which steeply dipping Silurian boulder conglomerates containing boulders of Ordovician sediments are overlain by almost horizontal Upper Devonian beds. 7

STRUCTUREBowling Orogeny

At the end of the Silurian period there was a mild orogenic epoch which caused revival of uplift along the old Benambran geanticline upon which the Lower Devonian beds rest with angular unconformity on the Silurian. In the geosyncline to the west, which includes the margin of the Murray Basin, there was no unconformity.

Taberabberan Orogeny

In the Middle Devonian there was a period of intense orogenic compression which stopped deposition in the Tasman Geosyncline everywhere in eastern Australia. It was probably during this orogeny that most of the folding and intrusion of granites in the Ordovician and Silurian sediments around the Murray Basin took place.

In central Victoria the Silurian sediments were subjected to intense folding which formed complex synclinoria and anticlinoria with north-south to N.N.W.-S.S.E. axes. The folding is most intense in eastern Victoria where there is some overthrusting. In most of the Silurian rocks dynamic metamorphism has produced cleavage, and low grade metamorphic minerals. A large amount of granite was emplaced in large batholiths and many of the granites in the Ordovician outcrops are probably of Taberabberan age, although in many cases this cannot be proved by intrusive contacts with Lower Devonian sediments.

In New South Wales the Taberabberan Orogeny produced a geanticline to the east of Cobar, which extended in a south-southeasterly direction at least as far as the Ardlethan area. In this geanticlinal belt the Silurian sediments were intensely folded and sheared and there were large intrusions, with a narrow elongated form parallel to the axis of the geanticline, of granite and porphyry, with gradation in places between the two types. There was mineralisation with copper and gold along this geanticline. It was to the west of this Taberabberan geanticline that the Upper Devonian marginal trough developed.

The Silurian rocks which must underlie the eastern part of the Murray Basin, along the strike of the intensely folded Silurian rocks in central Victoria, can be expected to be similarly sheared and cleaved, and affected by low grade metamorphism.

UPPER DEVONIAN - LOWER CARBONIFEROUS

After the uplift and erosion resulting from the Taberabberan orogeny a marginal trough developed between the stable Australian shield on the west and the mountain belt to the east. In this trough deposition of a thick series of clastic rocks began in the Upper Devonian and may have continued into the Lower Carboniferous. These rocks now crop out extensively around the eastern side of the Murray Basin, from a short distance east of Broken Hill round the eastern and southern margin of the basin as far as the Grampian and Black Ranges in western Victoria. The outcrops usually consist of relatively small ranges of steep hills formed by the massive sandstones rising either from low ground formed by softer older rocks or from the sandy plains of the Murray

Basin. The outcrops are in five main groups:

1. The West Darling District, where the sandstones form several ranges of hills east of Broken Hill.
2. The East Darling District, which has the greatest area of outcrop extending westwards from Cobar and southwards from the Darling River.
3. A large number of small outcrops on the eastern edge of the Murray plains extending southwards from the Lachlan River past Griffith and Narrandera almost as far as the Victorian border.
4. One uninterrupted large outcrop east and south of Mansfield in eastern Victoria.
5. The excellent outcrops in the rugged Grampian and Black Ranges in western Victoria.

Before the present survey remarkably little work had been done on this thick and widespread series. Some work had been done on the fish faunas found in the Mansfield outcrops, which showed that the sediments ranged from the Upper Devonian to the Lower Carboniferous, and some more detailed work has recently been done in the Grampians area by Mr. Spencer-Jones of the Mines Department, but this has not yet been published. Only a few rough estimates of thickness have been published and these are invariably much too low. On the present survey a considerable amount of attention was devoted to these beds and a large amount of new information was collected which made it possible for the first time for a fairly clear picture to be obtained of their thickness, correlation, conditions of deposition and structure. Because most of the facts and conclusions relating to these beds are completely new, the account given here will be fairly detailed. An outline of the main conclusions relating to sedimentation and structure is given at the end of the section, and this may be read alone without reference to the details of the several outcrops which are given first.

EAST DARLING DISTRICT

The Upper Devonian-Lower Carboniferous rocks of the East Darling area are described first because there the outcrops are most extensive and the sediments reach their greatest thickness. The outcrop is bounded on the east by the straight N.N.W.-S.S.E. Cobar fault which brings the Upper Devonian-Lower Carboniferous rocks against sheared and tightly folded Silurian sediments which have received important mineralisation of copper and gold. The Upper Devonian-Lower Carboniferous rocks are crossed by a complex pattern of folds and faults (Plate 4) and this factor, combined with the poor exposure, especially of the lower beds, has resulted in only a very rough estimate of the stratigraphic succession being made before the present survey. Most of the previous work on these beds was done in the eastern margin of the outcrop in the course of surveys of the Cobar Mineral field. Of this the most important work was by Andrews (1911) and Thomas^{son} (1953). The fullest account of the Upper Devonian-Lower Carboniferous rocks of the East Darling District was given by Mulholland (1940) who was, however, interested mainly in underground water. Mulholland included all the beds here called Upper Devonian-Lower Carboniferous in the Devonian and gave the following section, beginning at the top:-

Mulga Downs Stage	Massive sandstone and quartzite with subordinate shale. 800-1000 feet.
Amphitheatre Stage	Flaggy sandstone and quartzite with numerous Devonian marine forms. 300-500 feet. Red, green, grey, and yellow shales, grey tuffs, limestone, thin beds of quartzite. About 2000 feet. Fine grained quartzite with thin shale bands. About 2500 feet.

In the present survey a section was measured along the axis of a roughly north-south anticline, which was named the Belford Anticline, 30 miles southwest of Cobar. The beds can be seen to swing around the anticlinal axis without interruption in a way which makes it certain that strike faulting does not cause inaccuracy in the measurement. The section, augmented by some details from other outcrops, is given in Table 6.

TABLE 6

SECTION OF UPPER DEVONIAN-LOWER CARBONIFEROUS
ROCKS AT THE BELFORD ANTICLINE

From the Top

Division	Thickness (feet)	Lithology
Belford Beds	5,800	Medium grained, massive, white quartz sandstones. _____? Unconformity_____
Mulga Downs Beds		
V	700	Very massive, white and pale grey, conglomeratic coarse sandstone.
IV	700	Strongly false bedded, white medium and fine grained sandstone.
III	3,800	Massive, false bedded, coarse pebbly sandstone and conglomerate.
II	1,700	Strongly false bedded, white medium and fine grained sandstone with a few thin beds of dark red silty mudstone. Fish at Wuttagoona.
I	600	Massive, coarse conglomerate _____? Unconformity_____
Amphitheatre Beds		
Upper	(1,500)	(At Wuttagoona). Buff and pale grey, massive, medium grained sandstones.
	2,200	Flaggy, olive green, and grey-green muddy siltstones, mudstones and muddy fine sandstones showing graded bedding. No fossils.
Lower	3,100 +	Massive and flaggy, white, well sorted sandstones and quartzites with casts of brachiopods, lamellibranchs and crinoids.
Total:	20,100	

Some comment is necessary on the definition of the stratigraphic terms used and on the differences between them and the terms used by Mulholland. The terms Amphitheatre Beds and Mulga Downs Beds have been used following Mulholland, but the term 'beds' has been substituted for the rock-time term 'stage' which is inappropriate in this case. The term Mulga Downs Beds has a more restricted application than Mulholland's Mulga Downs Stage. It refers not to the whole of the sandstones overlying the Amphitheatre Beds but only to the lower part. The new term Belford Beds has been used for the upper part because of a difference in lithology and also because of evidence, mainly from the West Darling District, of an angular unconformity at the base of the Belford beds.

1. Amphitheatre Beds

Throughout most of their outcrop the Amphitheatre Beds form low, gently rolling ground covered with alluvium and residual lateritic deposits formed on the Tertiary peneplain. Small slabs of the muddy siltstones are scattered over the surface in many places, but measurement of dips is impossible and the pieces are usually deeply weathered and leached resulting often in incorrect description of 'brown shales', 'white shales' and 'red shales'. Also the limestone mentioned by Mulholland must be a secondary limestone as no limestone has been seen by the writer or recorded by anyone else in these beds. The best outcrops are northwest of Cobar around Booroondarra Station where the Amphitheatre Beds form low hills in which gullies expose unweathered rock. There are also many exposures along a line of intense shearing and folding which extend in a northeasterly direction west of Cobar and which has been called the Neckarbo Line. In this belt is the Amphitheatre Anticline, the Meadows Anticline and the Neckarbo Range further to the southwest. However in this shear zone the structure is too complicated for a section to be measured. At the Belford Section the exposures are poor and dips could not be measured on the low hills, with the result that the estimate of thickness depends upon the assumption that the dip along the axis of the anticline remains the same as in the basal bed of the Mulga Downs beds.

Lower Amphitheatre Beds: The one outstanding difference between the Lower Amphitheatre beds and the arenaceous deposits of the upper part is that the former are clean, well sorted sands consisting almost entirely of quartz. The grain size varies from medium to fine, and only in the basal beds cropping out in outliers east of the Cobar fault do coarse and conglomeratic beds appear. The sandstone is hard and firmly cemented with silica, but the actual description of these rocks as quartzites is not correct, being based on atypical silicified beds along the Neckarbo-Amphitheatre shear zone. The fossils are invariably preserved as casts and not one fragment of the original shell material has been seen. There is no direct evidence of when the decalcification took place, but it appears probable that it is only a superficial feature caused by deep weathering and leaching below the Tertiary peneplain. Not a trace of calcareous cement was found in the sandstone except for lime deposits of obviously superficial nature. Mulholland's description of tuffaceous sandstones could not be confirmed by any outcrops seen by the writer and since Mulholland's identification of tuffaceous beds was not confirmed by microscopic examination (personal communication) their presence must be regarded as doubtful.

The thickness of just over 3,000 feet estimated at the type section at Belford depends upon the assumption that the dip is the same as the base of the Mulga Downs beds, since the Lower Amphitheatre beds appear only as loose slabs on the surface of very gentle hills. However evidence from other sections shows that this estimate is not too high and might be too low. Along the Neckarbo shear zone at Beechworth Station, 70-80 miles southwest of Cobar, fossiliferous sandstones with steep dips of 70° to vertical crop out for a distance of at least three miles across the strike. Although it is obvious that there must be some repetition it cannot be doubted that at least several thousand feet of the fossiliferous sandstones are present. The sandstones cropping out here are noticeably more fossiliferous than those in the Belford section and in the Amphitheatre anticline, and this is probably caused by the fact that older beds, more highly fossiliferous than those at the other two places, crop out.

The Lower Amphitheatre Beds crop out along the Cobar fault where they form a straight ridge of steeply dipping sheared quartzite which Andrews (1911) called the Alley Beds. A parallel ridge of quartzite to the east he called the Water Tower Beds and included it in the Upper Devonian, as did Mulholland and Thomson. The writer has included the Water Tower Beds in the Silurian-Lower Devonian beds to the east of the Cobar fault because of the difference in lithology and the lack of fossils. The muddy, micaceous nature of the Water Tower beds and the interbedded brown shales indicate an environment of deposition unlike that of the Lower Amphitheatre beds.

The Lower Amphitheatre beds crop out thirty miles southeast of the Belford section in a narrow faulted slice between the outcrop of the Mulga Downs beds on the west and a Silurian granite on the east. These fossiliferous beds were called by Lloyd (1936) the Shenandoah Beds. They are included incorrectly by Mulholland (1940, p.21) in the Mulga Downs Beds. A few miles further south where Mulholland claimed the Mulga Downs Beds overlap the Amphitheatre Beds to rest directly on the granite, the contact is in fact faulted.

There are two outliers of the basal beds of the Upper Devonian preserved in the core of synclines folded into the Silurian rocks, one at Hermitage Plains and the other at Gunderbooka Mountain. The former outcrop, which is 45 miles southeast of Cobar, was visited in company with Mr. H. O. Fletcher of the Australian Museum, Sydney, and a good collection of well preserved fossils was made. Although the outcrop at Gunderbooka Mountain, 50 miles north of Cobar, was not visited by the writer, it seems clear from Mulholland's description that the sandstones belong to the Lower Amphitheatre Beds and are folded into the older rocks. Fossils were found in the sandstones, but Mulholland was induced to place the sandstones in the Mulga Downs Beds because of the presence of some conglomerate beds, a feature which is, however, present in the Lower Amphitheatre beds of Hermitage Plains.

Between the outcrop of the Shenandoah Beds and the outcrop at Hermitage Plains there is an outlier, in the form of a syncline, of quartzites and red and yellow shales which Lloyd (1936) called the Shume Beds and correlated with the Amphitheatre Beds, estimating a thickness of 6,000 feet resting unconformably on the Silurian. This outcrop was not visited by the writer. The correlation with the Amphitheatre Beds is considered unlikely because of the absence of fossils, compared with their abundance in the Shenandoah Beds to the west, and the Hermitage Plains outcrops to the east, and because the beds are baked by one of the series of porphyry intrusions which are almost certainly older than the Amphitheatre Beds.

The fairly abundant fauna of brachiopods and lamellibranchs in the Lower Amphitheatre Beds has been taken by palaeontologists as proof of an Upper Devonian age. Mr. H. Fletcher of the Australian Museum, who is at present engaged on a study of this fauna, agrees with that correlation.

Upper Amphitheatre Beds: The Upper Amphitheatre Beds have all the characteristics of flysch deposits. They are poorly sorted sediments consisting of a mixture of sand, silt and fine green mud in varying proportions. Graded bedding is present throughout the sediments, the thinner units in the finer beds causing a flaggy appearance in the outcrops. There is no lamination within each unit, but not uncommonly complicated contortions caused by slumping can be distinguished in the uniform sediment of the unit. At the base of the Upper Amphitheatre Beds fine sand predominates and the dominant sediment is a massive, very uniform, fine grained sandstone with a matrix of greenish mud and silt. The higher beds become progressively finer and there is also a decrease in thickness of the graded units to three inches and even less. However even in these flaggy fine grained beds the description of shale, which is usually used, is incorrect as a hand lens shows that even in those beds silt predominates over mud. The colour in all the fresh outcrops seen in the Booroondarra area is grey-green to olive-green changing to a yellow-green on weathering. The white, red, brown and yellow colours usually ascribed to these beds further south are the result of deep Tertiary weathering and leaching. No beds with an original red colour were seen in the Amphitheatre Beds and although some red beds may be present it is certain that green is the predominant colour. As in typical flysch deposits the Upper Amphitheatre Beds are completely devoid of organic remains and calcareous deposits.

In the area north of the Cobar-Wilcannia road the flaggy beds are overlain by massive, well sorted, medium grained yellow unfossiliferous sandstones containing clay inclusions. These beds have a superficial resemblance to some of the sandstones in the Mulga Downs Beds, but differ in lacking the strong false bedding of the latter. These medium grained sandstones are thickest at the northern part of this outcrop at Wuttagoona where they are involved, together with the basal conglomerate of the Mulga Downs Beds in the en echelon folding. The thickness of these is about 1000-1500 feet. The thickness decreases southwards till on the north side of the Wilcannia road the sandstones form only a small ridge at the base of the main escarpment which here is formed by the basal conglomerate of the Mulga Downs Beds. At the Belford section, 25 miles to the southeast, the sandstone has wedged out completely and the basal conglomerate of the Mulga Downs beds rests on the flaggy siltstones with only a little interbedded sandstone. This strongly suggests an unconformity between the Amphitheatre Beds and the Mulga Downs Beds.

It appears probable that not only have the sandstones at the top of the Amphitheatre Beds been removed by erosion in the Belford area before the deposition of the Mulga Downs Beds, but also that the top of the flaggy siltstones has been removed in the same area, as their thickness seems to be less than further north at Booroondarra. The thickness calculated for the Upper Amphitheatre Beds in the Belford section is 2,200 feet, and this is probably approximately correct, whereas in one fault block alone in the Booroondarra area 2,500 feet crop out. It is possible that in the Booroondarra area the muddy sandstones and flaggy siltstones are as much as 3,000 feet thick and the overlying medium grained sandstones are 1,500 feet thick, giving a total thickness for the Upper Amphitheatre Beds of 4,500 feet.

2. Mulga Downs Beds

The massive sandstones and conglomerates of the Mulga Downs Beds stand out over most of their outcrop area to form steep ridges which provide excellent exposures of the beds, making possible a good description of the stratigraphic succession and measurement of its thickness. The Mulga Downs Beds are a dominantly coarse grained series consisting almost entirely of sandstones and conglomerates, with only very small amounts of mudstone. Pronounced false bedding is present almost everywhere in the series and ripple marks are common in the finer beds. Flat, irregularly shaped inclusions of clay are common. The sandstones and conglomerates consist almost entirely of quartz and maintain this remarkable purity throughout the succession. Feldspar and mica are rare in the sandstones and mica is fairly abundant only in some of the mudstones and interbedded fine sandstones. Almost all of the sandstones and conglomerates have pale colours - white, pale grey or pale buff - and red coloured sandstone is uncommon. The matrix is everywhere siliceous, but the sandstone is not so quartzose as might appear from an examination of the surface of the outcrops which has often been silicified superficially.

The pebbles in the conglomerates are not large, seldom more than three inches in diameter and usually about one inch or less. By far the most abundant pebbles in the Belford section are those of white vein quartz. The pebbles in Group I (see Table 6) and most of Group III consist of vein quartz but in the top 700 feet of Group III there are numerous pebbles of dark grey and black chert which appear to be derived from the Silurian Ballast Cherts which crop out east of Cobar. In the Manara Range, 130 miles southwest of Cobar, where there are 2,300 feet of Mulga Downs Beds underlying the Belford Beds, with the lower part cut out by faulting, the conglomerates contain only pebbles of quartz, with the exception that one pebble of black chert was seen. This could mean either that the sediment in the Manara area was not derived from the Silurian rocks to the east, or else that the topmost Mulga Downs Beds containing the pebbles of black chert were removed before the deposition of the Belford Beds.

The mudstones in the Mulga Downs Beds are almost entirely confined to the lower part of Group II. They consist of dark red-brown and deep crimson silty mudstones with some interbedded flaggy sandstones. Another bed of mudstone was seen interbedded with the conglomerates near the top of Group III. There may be a few more beds of mudstone concealed in the valleys, but it is certain that they must be few and thin.

Evidence has been given in the section on the Amphitheatre Beds that the contact between them and the Mulga Downs Beds is unconformable. The contact was not seen to help to verify this point, as in the Belford area the basal conglomerate of the Mulga Downs Beds forms a steep escarpment at the foot of which loose blocks and rubble cover the contact.

The only fossils found so far in the Mulga Downs beds are fish found by the writer near the base of Group II on Wuttagoona Station. The fossils consist of casts in sandstone of large plates of several species of large armoured fish. A preliminary examination showed that this is virtually a new fauna to Australia and it appears to be of Upper Devonian age. Preliminary work suggests that it might be transitional between known faunas of Upper Devonian and Lower Carboniferous age.

3. Belford Beds

The Belford Beds are a series of white, medium and fine grained, false bedded sandstones which overlies the Mulga Downs Beds at the Belford Anticline. They are noticeably softer than the Mulga Downs Beds, forming a series of low, rounded ridges, separated by flat, alluvium filled valleys. The sediments which do outcrop are very uniform in composition, the only types other than the medium and fine sandstones being a bed containing a few pebbles near the bottom and a massive bed approaching coarse grade near the top.

The possibility of an unconformity at the base of the Belford Beds is suggested by the presence of a strong angular unconformity at what seems to be the same horizon in the Mootwingee-Gnaltia area in the West Darling District. The only evidence for an unconformity at the Belford anticline is the change in lithology, the decrease in hardness above the contact and the slight decrease in dip from 22° to 18° .

The only other place at which the Belford Beds have been recognized is at the Manara Range, where 3,400 feet of the beds overlie the Mulga Downs Beds. Here also there is a suggestion of an unconformity at the base of the Belford Beds, as the conglomerates with black chert pebbles present at the top of the Mulga Downs Beds at the Belford section are absent. Both here and at the Belford section the top of the Belford Beds cannot be seen because of the cover of sand dunes, and the total thickness, therefore, is not known.

4. Structure

The structure of the Upper Devonian-Lower Carboniferous rocks of the East Darling district is a complex arrangement of faults in two main directions, and folds, also in two directions, approximately at right angles to each other. With the help of aerial photographs it was possible to elucidate for the first time the structure of the rocks in the area covered by the photographs, which extends for 35 to 40 miles west of the Cobar fault (Plate 4). Previously only the Amphitheatre Anticline and the Western Fold had been recognized and on this evidence no attempt could be made to analyse the causes of the various structures and their relation to each other.

The most strongly developed series of folds has axes with an average direction of N 20° W, roughly parallel to the Cobar Fault, but varying in direction from north-south almost to N.W.-S.E. The distribution of this series of folds is significant. It is restricted to a belt 30 miles wide on the west side of the Cobar Fault, and in this belt there is a marked reduction of the intensity of the folding from east to west. The most intense folding is apparent in the Western Fold immediately to the west of the Cobar fault near Cobar. This fold was first described by Thomson as the Western Anticline (Thomson, 1953), but the vaguer term fold is used here as it is considered possible that the fold might be in fact a syncline. Along the eastern flank, the fossiliferous Lower Amphitheatre Beds form a ridge of sheared quartzite which clearly has a dip of 70° - 80° to the east. The same quartzite crops out on the flat plain on the west flank of the fold and it forms a low ridge to the south which shows that the outcrop closes in that direction. However only one good dip can be seen on this western flank, at the side of the Wilcannia road, and it is to the west at 65° , suggesting that the fold is anticlinal. It is possible however that the fold is a syncline with the east limb overturned. On the western limb outcrops with north-easterly dips on the eastern side of the Amphitheatre Anticline continue up to a point close to the 65° westerly dip, suggesting that the latter is a local anomaly. Also at several places the flat

will drag folds into
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28.

ground in the middle of the fold is covered with pieces of weathered argillaceous rock which might be Upper Amphitheatre Beds and which would, in that case, prove the synclinal nature of the fold. An overturned eastern limb would be consistent with the structural environment, on the deeper side of an asymmetric basin bounded by a reverse fault, the Cobar Fault.

Folding in the same north-northwest direction is clearly visible in the hills formed by the Mulga Downs Beds between Belford and Buckinbool Mountain. The Belford Anticline, the syncline to the east and the Buckinbool syncline all show a swing in the direction of the axis from northwest at the northern end of the outcrops to north-south further south. The Bulgoo Anticline differs in having a perfectly straight axis, with a direction of about N 20° W, and in having very steeply dipping limbs. Another noteworthy feature is that in the area where the structure of the Mulga Downs beds can be clearly seen on the aerial photographs the folded beds are not cut by one fault.

A series of three elongated domes or short anticlines arranged en echelon is very well exposed in the bare rocky hills above Wuttagoona Homestead, 40 miles northwest of Cobar. The anticlines are elongated in a direction of about N 25° W and a line joining their culminations has a direction very slightly west of north. The anticlines are all very similar in form and are clearly related in origin. The southwestern limb is the steeper, and along much of its length is a normal fault with downthrow to the southwest. Further to the northwest the fault passes gradually into a steep monocline which decreases in dip and swings around the nose of the anticline into a similar fault on the southwestern flank of the next anticline. These faults are clearly tensional fractures. On a southerly continuation of a line joining the culminations of the anticlines, and at a distance similar to that separating each of them, is a kink in the outcrop of the steeply dipping beds at the junction of the Amphitheatre and Mulga Downs Beds which looks like a drag fold, and appears to be related in origin to the three anticlines to the north. The form of these folds shows that the sediments behaved plastically when deformed and had therefore probably been only slightly lithified at the time of deformation. The en echelon arrangement of the folds and the restriction of the folding to one relatively narrow zone suggests that the folding was caused by shearing stress transmitted to the soft sediments by a more rigid basement, perhaps along the line of a fault in the basement with horizontal displacement. Within this belt of folding, as in the Belford-Buckinbool area, the sediments have yielded to deformation almost entirely by folding; the only faults are the small tension faults replacing monoclines.

The outliers of Lower Amphitheatre Beds east of the Cobar Fault are preserved along the cores of fairly tight synclines with axes roughly north-northwest, parallel to the Cobar Fault. At Gunderbooka the sandstones are folded into a syncline with a southerly pitch, according to Mulholland, with dips of 25°-40° on the western limb and lower dips on the eastern limb. The Hermitage Plains inlier also consists of a southerly pitching syncline with dips of about 40° on the eastern limb and, as at Gunderbooka, a steeper western limb. The way in which these Upper Devonian Beds are infolded into the basement of Silurian and perhaps Lower Devonian rocks shows that during the deformation of the Upper Devonian Beds the basement, although already tightly folded, still was able to yield by folding.

The second series of folds, which have axial direction varying from east-west to northeast-southwest, are confined to a narrow belt with a direction of N 40° E. The belt as a whole is

Closest
series of
Cobar
synclines

anticlinal, but in it the individual folds tend to be arranged en echelon. The best exposed of these en echelon anticlines is the Amphitheatre Anticline which is fairly well exposed for eight miles along the axis where the quartzites of the Lower Amphitheatre Beds rise above the flat plain formed by the Upper Amphitheatre Beds. At the western end of the outcrops the axis has a direction of E.N.E.-W.S.W. and the pitch to the southwest, as is clearly shown by the quartzite curving around the nose of the anticline and forming the 'amphitheatre'. The dip is 35° on the southern limb and steeper, about 45° , on the northern limb. Further east the axis swings gradually around to a direction slightly north of east. The eastern end of the anticline has a steeper northern limb, as at the southwesterly plunge, but the closure to the east is not as symmetrical as has been shown on previous maps. Several W.N.W.-E.S.E. faults cut obliquely across the eastern nose of the anticline and in the slices bounded by these faults the dip steepens gradually away from the anticline till, at the most northerly outcrops, the beds are vertical. In this steeply dipping northern limb of the anticline the flaggy Upper Amphitheatre Beds show in many places complicated drag folding.

A similar anticline was found 15 miles to the south-east and named the Meadows Anticline. This is poorly defined by a few low ridges rising above the drift covered plain and was mapped entirely from aerial photographs. The portion of the axis which can be defined is fairly straight, with a direction of $N 70^{\circ} E$, and the pitch is to the east.

Further to the southwest again there is a belt of steeply dipping Amphitheatre Beds bounded on the south by the Neckarbo Range formed from Mulga Downs Beds with a strike of $N 40^{\circ} E$ and the dip away from the deformed belt. The strike of the Amphitheatre Beds varies from northeast-southwest to east-west and the dip is 50° to 90° both to north and to south. This belt of steeply dipping Amphitheatre Beds is five miles wide in places and it is clear that the beds are repeated by folding or faulting or both, perhaps by structure similar to the Amphitheatre Anticline but steeper. The report of mineralisation in this area suggests the possibility that even some mineralised Silurian rocks may have been brought up along the shear zone in the middle of the Upper Devonian outcrop.

Further southwest along the same line, beyond a gap caused by sand dunes, the steeply dipping beds of the Manara Range, with a northeasterly strike, show that the Neckarbo shear zone continues at least as far as that point. The beds of the Manara Range differ from those of the Neckarbo Range in dipping to the northwest, towards where the Neckarbo Fault is presumed to pass under the drift. A possible continuation of this northeast-southwest shear zone as far as the middle of the Murray Basin is suggested by geophysical evidence, and will be considered later.

Both Mulholland and Thomson showed this deformed zone at its northeastern end and as swinging to an east-west direction through the Amphitheatre Anticline. However the presence of a strong shear zone in the Silurian rocks on the north side of Mount Drysdale suggests that the Neckarbo Fault continues in a straight line parallel to the Darling River through this shear zone. The structure at Mount Drysdale is very similar to that along the Neckarbo Fault in the Upper Devonian-Lower Carboniferous Beds. On the southern side of the shear zone there is a tight syncline in the Silurian sediments with an axial direction of $N 40^{\circ} E$, parallel to the Neckarbo Fault but almost at right angles to the main folds in the Silurian rocks a few miles to the south.

The description of this complex belt of steeply dipping beds and en echelon folds as a 'fold axis' by Mulholland is clearly inadequate. The only explanation of the structure which fits the evidence is that the line is basically a fault line with horizontal displacement and that the folds are related to the horizontal movement. Similar structures have been described in the Carboniferous of Scotland (Anderson, 1942, p.90 et seq.) and the mechanism of these folds accompanying wrench faults with reference to American examples has been discussed more recently (Moody and Hill, 1956). The limited amount of evidence available suggests that close to the main fault the dip is usually steep and the strike parallel to the fault, and that the fold axes tend to diverge from the fault in a curve. For example the Mount Drysdale syncline is close to the fault and is parallel to it. The Meadows Anticline is further away and has an axial direction of N 70° E, while the Amphitheatre Anticline is further away and at its eastern end has an axial direction of almost east-west. On the other hand the Amphitheatre Anticline might be too far from the Neckarbo Fault to be related to displacement along it and may be related to a splay fault diverging from it.

The Mount Drysdale Syncline was probably initiated at the same time as the structures in the Silurian rocks of the Cobar area, that is in the Middle Devonian Taberabberan orogeny, and since it has been concluded that this fold is related to the Neckarbo Fault, it follows that this fault was in existence during the Taberabberan orogeny. The gold mineralisation at Mount Drysdale is probably related to the Taberabberan movement along the fault. It is also interesting to note that cross-folding, which might possibly be similar in origin to the Mount Drysdale Syncline, appears to play an important part in the localisation of the ore in the Cobar mineral field (Thomson 1953, p. 868).

There are three other important fault lines in the East Darling District parallel to the Neckarbo Fault. A large fault is thought to follow the line of the Darling River in the long straight stretch from Menindee to Louth and probably a long way further to the northeast. The line is a continuation, offset a small distance to the south, of the important Redan Fault which bounds the Broken Hill massif on its southern side. At Louth there is a small outcrop in a gully near the river of sediment which is highly sheared and crossed by quartz veins. This is of Silurian age according to Mulholland, although it is to the west of a projected continuation of the Cobar Fault. To the northeast of Louth a continuation of the Darling line forms the southern boundary of the Great Artesian Basin. This evidence is not very abundant, mainly because of the cover of Quaternary deposits, but it is enough to indicate that there is an important line of movement along this section of the Darling River.

Another fault parallel to the Neckarbo Fault appears to offset the Cobar Fault 15 miles to the west 25 miles south of Cobar. Exposures are poor in this area, but the offset of the Silurian-Upper Devonian boundary fault is a fact, and there is little doubt that this offset takes place along a fault of the same set as the Neckarbo Fault.

Further south there is evidence of a very important parallel line of movement along the line of the Lachlan River which causes a swing in the strike of the Mulga Downs Beds in the narrow outcrop west of the boundary fault from north-south to northeast-southwest. This structural line along the Lachlan River is discussed in more detail later.

The second major direction of faulting is parallel to the Cobar Fault, varying from N 20° W to almost north-south. The Cobar Fault is considered by Thomson to be a reversed fault with a dip roughly parallel to that of the eastern flank of the western fold, that is 70°-80° to the east. This agrees with the hypothesis that this eastern limb is overturned. Thomson shows several lines of shear diverging from the Cobar Fault at an acute angle having a direction varying from approximately parallel to the Cobar Fault to N 10° E.

The evidence from boreholes shows that there is a large fault parallel to the Cobar fault which forms the southwestern boundary of the Upper Devonian-Lower Carboniferous rocks under the Tertiary and Quaternary cover south of Wilcannia. Boreholes on the western side of the fault went from Tertiary into 'slate' which is probably of Proterozoic or perhaps Silurian age. This fault is on a continuation of the large Koonenberry Fault north of the Darling River, offset for a short distance to the west, probably by the fault along the Darling River.

WEST DARLING DISTRICT

There are many outcrops of Upper Devonian-Lower Carboniferous Beds in the West Darling District, where they usually stand out to form fairly steep hills surrounded by the lower, smoother hills formed by the underlying Proterozoic sediments, and the gently undulating or flat plains formed by the overlying Cretaceous and Quaternary sediments. In this bare, arid region the structure of the massive sandstones shows very clearly on the aerial photographs, and the study, made for the first time, of the area which has been photographed yielded a very good picture of the structure. (Plate 2). The only previous description of any importance of these beds was by Kenny (1934) who called them Mootwingee Series, dividing them into a lower Gnalta Stage and an upper Mootwingee Stage which was thought to rest unconformably on the Gnalta Stage and to overstep it on to the Proterozoic. The present survey has resulted in radical alterations to this succession.

A section was measured in the Mootwingee Range, a range of hills in which the beds have a northwesterly strike with the dip to the southwest. The only major interruption in this section is a strike fault which repeats the outcrops; but correlation can easily be made across the fault to enable the section to be calculated. It is given in Table 7. Kenny's term Gnalta Stage has not been used because in his type area in the Gnalta hills and in other places the sediments are not at the base of the succession but are the upper beds overstepping the lower two divisions to rest directly on the Proterozoic. The term Mootwingee beds has been retained for the middle division.

1. Lingula Beds

The lowest beds, which have been given the name of Lingula Beds, consist of two lithological divisions, a lower of sandstones and an upper of muddy siltstones, similar to the two divisions of the Amphitheatre Beds with which they are correlated.

However there are important differences in the lithological details. The lower division consists of massive pale grey medium and fine hard siliceous sandstones composed of clean, well sorted quartz grains. Ripple marks are fairly common. There is a little interbedded greenish mudstone and at the top of the division a hard bed of conglomerate 60 feet thick which stands up to form a sharp spine among the steeply dipping beds on the east side of the Mootwingee Range. In the sandstone there are numerous contemporaneous animal burrows cutting across the bedding and trails parallel to the bedding. The only other fossils found are some specimens of the large triangular Linguloid, Trigonoglossa.

The upper division of the Lingula Beds consists mainly of rather soft, poorly bedded sediments consisting of a poorly sorted mixture of fine sand, silt and pale olive green mud. Interbedded with these green beds are dark, purplish, highly ferruginous beds consisting of sand grains in a ferruginous matrix. In some of the green beds linguloids are very abundant, but fossils were not found in any of the

TABLE 7

SECTION OF UPPER DEVONIAN-LOWER CARBONIFEROUSROCKS IN THE MOOTWINGEE RANGE

(From the top)

<u>Division</u>	<u>Thickness (feet)</u>	<u>Lithology</u>
<u>Ravendale Beds</u>	3,600	Uniform, white, false bedded, medium and fine sandstones, with scattered small pebbles in some beds.
<u>Unconformity</u>		
<u>Mootwingee Beds</u>		
<u>VII</u>	1,300	Massive, boulder conglomerate.
<u>VI</u>	2,200	Massive, white medium and fine grained sandstone with some inter-bedded conglomeratic sandstone. Very little dark red, silty mudstone.
<u>V</u>	600	Very massive, pale grey, coarse conglomeratic sandstone.
<u>IV</u>	500	White, false bedded, medium and fine grained sandstone with a few animal burrows.
<u>III</u>	2,400	Massive, pale grey, coarse pebble conglomerate.
<u>II</u>	1,000	White, strongly false bedded medium and fine sandstone.
<u>I</u>	1,700	Massive, pale grey, coarse, conglomeratic sandstone with some soft beds of dark red, muddy, micaceous fine grained sandstone.
<u>Unconformity</u>		
<u>Lingula Beds</u>		
Upper	2,300	Olive-green, muddy, fine grained sandstones and siltstones, inter-bedded with some dark purplish, highly ferruginous sandstones. Abundant linguloids in some beds.
Lower	2,700 *	White and pale grey, well sorted, medium grained sandstone with very little interbedded greenish silty mudstone. Animal burrows and tracks common in the sandstones. A few <u>Trigonoglossa</u> .
Total:	18,300	

purplish beds. In the lower beds the linguloid is a Trigonoglossa indistinguishable from those in the sandstones of the lower division while in the upper beds there is a smaller oblong Lingula.

✓ The total thickness of the Lingula Beds is not known because at the type section the contact with the Proterozoic is a fault of unknown throw. A thickness greater than the 2,700 feet estimated for the lower division at the type section may be present at the outcrops of folded beds at the northeastern corner of the Mootwingee Range.

2. Mootwingee Beds

The Mootwingee Beds consist of 9,700 feet of very massive beds, almost entirely sandstone and conglomerate with only a very small thickness of interbedded mudstone, three or four hundred feet at most. The lithology is very similar to that of the Mulga Downs Beds, which are of the same age, in particular in the highly siliceous character of the sediments, with no feldspar, and mica only in the interbedded argillaceous beds. The most significant difference is in the composition of the pebbles in the conglomerates. There are small, sub-angular pebbles which are all of vein quartz, as in the Cobar area. The larger, well-rounded pebbles, on the other hand, are almost entirely of quartzite, whereas in the Cobar area the pebbles were almost all of vein quartz in the lower beds and were of vein quartz and Silurian chert in the upper beds. There are no pebbles of Silurian chert in the Mootwingee section. The quartzite pebbles appear to be derived from the Proterozoic and perhaps Cambrian and therefore indicate that the source of the sediment was to the west. The only traces of life found in the Mootwingee beds were some animal burrows in the medium grained sandstone of Group IV and one similar burrow found in medium grained sandstone in Group VI. (See Table 7).

The possibility of an unconformable contact between the Mootwingee beds and the underlying Lingula beds is suggested by the presence of an unconformity at the same horizon, that is between the Amphitheatre Beds and the Mulga Downs Beds, in the Cobar area, which is almost in the middle of the sedimentary basin. There is evidence for such an unconformity on the northeastern side of the Coppermine Range where the Mulga Downs Beds appear to rest directly on the Proterozoic, or at least to be separated from it by only a very thin development of the Lingula beds. However this suggestion would need to be confirmed by more detailed field work than was done on this survey.

3. Ravendale Beds

The Ravendale Beds are noticeably softer and more loosely cemented than the Mootwingee Beds. In the outcrop along the western margin of the Mootwingee Range the beds consist almost entirely of soft, white, loosely cemented, medium and fine sandstones. The only coarse sandstone is in one bed near the base. In the southern half of the range, south of Mootwingee Homestead, the Ravendale Beds overstep on to successively lower beds of the Mootwingee Beds until at the southern end of the range, over the dome structure, they rest on Group IV of the Mootwingee Beds. The way in which the overstepping is restricted to this dome shows that the doming movement was active before the erosion and the deposition of the Ravendale Beds.

The Gnalta Hills, to the northeast of the Mootwingee Range, consist of a very gentle basin structure with dips usually 10° or less, in beds which are indistinguishable from the Ravendale Beds, apart from the presence, mainly near the base, of some small quartz pebbles scattered through the medium and fine sandstone. These beds are quite

unlike the Lingula Beds and the lower parts of the Mootwingee Beds and their correlation with the Ravensdale Beds seems fairly certain, despite the radical changes this causes in Kenny's ideas of stratigraphy and structure. As these beds rest unconformably on the Proterozoic, it follows that in the earth movements following the deposition of the Mootwingee Beds and preceding that of the Ravensdale Beds, the area of the Gnalt Hills was raised, probably along faults, at least 15,000 feet and the Lingula Beds and Mootwingee Beds were completely stripped from the fault block. In the Noonthorungee Range to the northwest of the Gnalt Hills a study of the aerial photographs shows the almost horizontal Ravensdale Beds resting on steeply dipping Mootwingee Beds. Thus it appears that a large part of the deformation of the Lingula Beds and Mootwingee Beds took place before the deposition of the Ravensdale Beds.

4. Correlation

The three divisions of the Upper Devonian-Lower Carboniferous beds in the Mootwingee area have a strong and obvious similarity to the three divisions in the Cobar area and, although direct fossil evidence is lacking, the correlation of the three divisions at the two places seems to be fairly certain. There is great similarity between the Amphitheatre Beds and the Lingula Beds in consisting of a lower division of well sorted sandstone succeeded by an upper division of poorly sorted mudstones and siltstones with a dominantly green colour, although it cannot be assumed that the change from one facies to the other was contemporaneous at the two places. The thickness of the two divisions at the two places given in the measured sections are almost exactly the same although the Cobar section might be expected to be thicker, being almost at the centre of the sedimentary basin. However the lower sandstone division might be much thicker in the Cobar area than the minimum figure given. The lithology and fossil content at the two places reveals the different conditions of deposition. The fauna of brachiopods, lamellibranchs and crinoids found in the Lower Amphitheatre Beds is completely absent in the Mootwingee section where the presence of only linguloids and various animal burrows shows that conditions there were not suitable for an abundant and varied fauna. Conversely during the deposition of the Upper Amphitheatre Beds the muddy waters in the Cobar area, periodically stirred up by turbidity currents, made life virtually impossible, whereas in the Mootwingee area, on the less active flank of the basin, linguloids were able to flourish periodically.

The sandstones and conglomerates of the Mulga Downs Beds have the same lithology as those of the Mootwingee Beds, with the exception of the different types of pebbles already discussed, leaving no doubt that they should be correlated. It is not considered possible at present to make a correlation between the alternating coarse and finer groups at the two places because the conformities at top and bottom of the beds might result in an unknown thickness being absent at the bottom because of overlap or at the top because of erosion at either place, and also because rapid wedging out of beds is to be expected in this type of sediment.

The Ravensdale Beds are very similar in lithology to the Belford Beds, except that in the former there are some small quartz pebbles scattered through the finer sediment. In both places the presence of well rounded quartz grains with 'frosted' surfaces suggests the influence of aeolian action.

5. Structure

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The dominant structures of the area are faults, and there are only a few folds. Throughout most of the outcrops in the West Darling District, that is the Mootwingee-Koonenberry group of outcrops (Plate 2) and those on the east side of the Broken Hill Archean outcrops, faults with a north-northwesterly direction are by far the most numerous. In the south of the district there is a belt parallel to the Darling River and extending about 20 miles from it in which the strike is influenced by the easterly continuation of the Redan Fault on the south of the Broken Hill massif, and is parallel to this fault and the Darling River, that is northeast. In this southern part of the district exposures are not good and in the absence of aerial photographs little of the structural detail could be made out.

In the Mootwingee-Koonenberry area the dominating structural feature is the Koonenberry Fault which extends in nearly a straight line from west of Tibbooburra (the Waratta Fault) for 120 miles to the southern end of the Coppermine Range where it turns to a southerly direction for 12 miles before curving back to approximately its original direction for a short distance and then disappearing under the Quaternary cover. At the northern end of the straight stretch the direction is N 20°W and in the south between Koonenberry Mountain and the Coppermine Range it turns to N 33°W. At the place where the fault changes to a southerly direction, it is not possible to see whether another branch continues on the same south-southeasterly course because of drift cover. However, about 15 miles further to the south-southeast a few small outcrops of Upper Devonian-Lower Carboniferous Beds appear from below the Cretaceous and Quaternary cover and they have a northeasterly strike, suggesting that the Koonenberry Fault does not continue in its original direction as far as this point.

Koonenberry Mountain is a long, narrow, sharp-edged ridge with a length of eight miles and a maximum width of less than half a mile which rises abruptly for several hundred feet from the gently undulating country formed by the Proterozoic mudstones. It is composed of very hard, whitish quartzites, assumed on lithological grounds to belong to the Mootwingee Beds, which are vertical or have steep dips to the east-northeast. Along the eastern side of the mountain is a zone of gouge 50-75 yards wide which is evidently caused by a fault of very large displacement. There is also a large fault along the western side of the mountain which is accompanied by heavy shearing. For several miles south of the main mass of the mountain there is a continuation of the ridge of quartzite, faulted on both sides against Proterozoic, which is 100 yards or less wide, too narrow to be shown on the map. The shear planes in the gouge on both sides are approximately vertical and therefore the fault planes must also be approximately vertical, although they presumably converge slightly downwards.

The only possible explanation of the features of this fault zone - the straight fault trace, the severe shearing, the vertical attitude and the long, very narrow slice faulted downwards on both sides - is that there has been a large horizontal displacement along the fault zone. Identical phenomena have been found along the well known San Andreas wrench fault in California. A recent publication (Wallace, 1949) describes a narrow rift along the line of the fault in which there is a long slice of vertical beds, only a quarter of a mile wide, downfaulted on both sides. In this case the slice is composed of Pliocene sediments which prove that their structure is related to the horizontal movement, as the fault is known to have been moving with horizontal displacement since that time. Similar narrow rifts have been found in New Zealand along the Wellington Fault which is a large wrench fault still moving at the present day (Lensen, 1958). This type of narrow slice faulted

downwards in a zone of shearing can perhaps not only be taken as proof of the horizontal nature of the displacement in the present instance, but also may be taken elsewhere as a diagnostic feature of such wrench faults.

At the southern end of the outcropping part of the Koonenberry Fault, where it makes a convex curve to the west, there is on its eastern side a dome structure in the Mootwingee Series, the Menamurtie Dome, which is slightly elongated in a northeasterly direction. A possible explanation of this structure is that it was formed by a northwest to southeast compression resulting from the resistance provided by the projecting section on the block on the eastern side of the fault to the southerly movement of the block on the western side.

There is a powerful fault along the eastern side of the Mootwingee Range which is roughly parallel to the Koonenberry Fault and which is probably also a wrench fault. In places along the eastern side of the range the lower division of the Lingula beds has many slickensided surfaces most of which indicate relative movement in a nearly horizontal direction. A fault which diverges at an acute angle and cuts through the middle of the range also appears to be one of the same set of wrench faults. Near the southern end of the range the fault separates two half domes with the axes offset a distance of two miles, a feature which could not be explained by normal faulting. The direction of movement indicated by the offset of the dome is dextral, whereas the movement postulated for the Koonenberry Fault is sinistral. As the movements of the same age in parallel wrench faults must be in the same sense, it is possible that the two half domes are not parts of one original whole, but developed independently on opposite sides of the fault as a result of the horizontal displacement of the two sides of the fault.

Same
as Corona
Fault
to W.
Not shown
on Plate 1A

Age of the Movements: A comparison of the structure of the Ravendale Beds with that of the Lingula Beds and Mootwingee Beds shows that most of the deformation of the lower two divisions took place before the deposition of the Ravendale Beds. It has already been described how the overstepping of the Ravendale Beds over the dome structure at the southern end of the Mootwingee Range shows that this dome was moving before the deposition of the Ravendale Beds. As it has been concluded that the dome and basin structure close to the fault is related to the horizontal movements, it follows that the wrench faults were moving before the deposition of the Ravendale Beds. It thus seems that after the deposition of the Mootwingee Beds there was a period of intense compression, which resulted in horizontal movement, probably sinistral, along the Koonenberry Fault and several subsidiary faults. There was also raising, lowering and tilting of the fault blocks. Subsequent erosion removed all of the Lingula Beds and Mootwingee Beds from the higher parts of the blocks.

The post-Ravendale Beds deformation was much more gentle. In the Gnalta Hills a very gentle synclinal structure was formed with its axis parallel to the Koonenberry Fault. Along the western side of the Koonenberry Range there was more deformation, dips being as much as 37° , and there is evidence in the southern part of the range that there was more movement along the wrench faults causing gentle folding in the adjacent sediments.

LACHLAN-NARRANDERA AREA

In the area between the Lachlan River and the Victorian border there are extensive outcrops of Upper Devonian-Lower Carboniferous beds along the margin of the Murray Basin which rest unconformably on Ordovician sediments intruded by numerous granite batholiths.

The extent of the outcrops is greatest in the north of the strip and it decreases southwards as far as Narrandera, south of which there are only a few outliers within the Ordovician outcrop. Little work was done on this strip of country till recently when geologists of the Mines Department of New South Wales began work on the mapping of three 4-mile sheets which cover this area, the Eubalong, Narrandera and Jerilderie sheets. These sheets are not yet published, but the provisional sheets were made available to the writer by the Mines Department. This mapping was sufficient for the purpose of the present survey and the writer's work was almost entirely confined to the measurement of a section.

A complete section could not be measured at any one place among the isolated hill masses separated by alluvial plains and the section which was measured was compiled from two places. (Table 8). The lower beds were measured northeast of Ardlethan on the western flank of a syncline, which is bounded on the west by a large fault with a direction of N 15° W. The unconformity at the base of the Upper Devonian is clearly visible at the town of Ardlethan and again further north at the nose of the syncline showing that there are no lower beds than those outcropping which are cut out by faulting. The beds are well exposed except for some soft beds near the base which form a flat, alluvium filled valley along their outcrop.

TABLE 8

ARDLETHAN - COCOPARRA SECTION

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From the top.

<u>Division</u>	<u>Thickness (feet)</u>	<u>Lithology</u>
Measured in Cocoparra Ra.		
<u>VIII</u>	800	Massive, coarse sandstone and conglomerate. Colour is buff, pink or red. One or perhaps two thin beds of purplish silty mudstone. Coarse pebble conglomerate at the base, 30 feet thick.
<u>Unconformity</u>		
<u>VII</u>	300	Poorly bedded, dark purplish red micaceous silty mudstone and muddy siltstone. Some fine sandstone, mainly near the top. Colour changes to pale brown near top.
<u>VI</u>	500	Massive coarse sandstone with scattered small pebbles. Some beds of medium grained sandstone.
<u>V</u>	900 +	Well bedded, flaggy in places, pale brown micaceous, fine and medium grained sandstone.
Measured in Ardlethan Section		
<u>IV</u>	900 +	Massive, pink, coarse sandstone with some interbedded medium grained sandstone.
<u>III</u>	1,900	Pink, pale red and some dark red, false bedded medium and fine grained sandstone.
<u>II</u>	2,200	Presumably softer sediments which are not exposed in the section.
<u>I</u>	700	Massive, buff, coarse, conglomeratic sandstone.
<u>Unconformity</u>		
Total:		8,200 +

The upper part of the section was measured on the eastern side of the Cocoparra Range, 40 miles to the west-north-west of Ardléthan, where the beds have a very gentle westerly dip. Since there are no beds in the Ardléthan section like the fine sandstones of Group V and the purple mudstones of Group VII at the Cocoparra Range, it seems certain that they are not represented in the former section and therefore that in the compilation of the total section the sections at the two places should be added together. It was not possible to calculate the thickness of the beds intermediate in age between those of the two parts of the section, but it is probably not large.

The unconformable nature of the boundary between Groups VII and VIII is clearly shown by the inclusion within the lowest few feet of the coarse conglomerate of fragments derived from the erosion of Group VII. However the unconformity does not appear to be a large one since Group VII had not been subjected to much erosion before the deposition of Group VIII. The mudstones continue under the basal conglomerate of Group VIII along the eastern side of the Cocoparra Range, and they reappear again around the syncline at McPherson Range north of Griffith, 20 miles further west, where they are used for brick making. A railway cutting at Leeton, 30 miles south of the Cocoparra Range, exposes 60 feet of mudstones, siltstones and fine sandstones which probably belong to Group V. The beds are now white and kaolinitic but odd patches of purple colouration show that this is the original colour and that the white colour is caused by Tertiary weathering. Further south, in a railway cutting south of Narrandera, there are similar white beds which are probably of the same age. In them were found poorly preserved casts which look like organic structures, but which are probably not identifiable. These are the only fossils found in the Upper Devonian-Lower Carboniferous rocks of the Lachlan-Narrandera area, apart from the root impressions in Group V at the Cocoparra section.

Correlation

There seems to be little doubt that the sandstones and conglomerates of the Ardléthan-Cocoparra section should be correlated with the Mulga Downs Beds and perhaps the Belford Beds of the Cobar area and that the Amphitheatre Beds are completely absent. There is, therefore, a southerly wedging out between the Cobar area and the Ardléthan section of at least 7,000 feet of sediments at the base of the Upper Devonian.

While the sandstones and conglomerates of the Ardléthan-Cocoparra section have a general similarity to those of the Mulga Downs Beds, there are some important differences. The most obvious is that at the former locality a red colouring is common, varying from pink to dark red, whereas in the Mulga Downs Beds there is not much red sandstone. Another difference is that in the Ardléthan section feldspar is present in small amounts in some of the sandstones and mica is fairly common, whereas in the Cobar area feldspar was not seen in any of the sandstones and mica is restricted almost entirely to the few interbedded muddy, fine sandstones. There is a similarity in the upward change in composition of the pebbles. In the basal conglomerate of Group I the pebbles are all of vein quartz and white quartzite. In the higher conglomerate of Group V the pebbles are mostly of black and white quartzites and cherts derived from Silurian and Ordovician rocks uplifted to the east. A similar change takes place in the pebble content of the Mulga Downs Beds, but did not necessarily take place at the same time.

There are no beds having the same lithology as the Belford Beds at the top of the succession. However, considerable lateral changes in lithology are to be expected in this type of sediment and it is not possible to say whether beds of the same age as the Belford Beds are present.

Structure

The outstanding feature of the structure compared with that of the Cobar areas is that folding and faulting are much gentler. The beds are in shallow folds with north-northwesterly axes and with dips usually less than 25° except near faults. The only large fault near the margin of the Murray Basin is that at Ardlethan, which has a direction of N 15° W parallel to the Cobar fault to the north and on almost the same line. There is no sign of the northeasterly cross faults and related east-west folds which are such an outstanding feature of the area west of Cobar. The evidence of thinning and overlap and of the gentle structure shows that the area south of the Lachlan River was more rigid and less subject to subsidence than that to the north where the thick sediments of the Cobar area accumulated.

MANSFIELD-MITCHELL RIVER AREA

This outcrop of the Upper Devonian-Lower Carboniferous beds is a roughly parallel sided belt, 30 miles wide, which extends from the edge of the Murray Basin for 100 miles to the southeast as far as the Gippsland Basin where it disappears under Tertiary sediments. It is all rough mountainous country with a sparse population and because of this and the lack of valuable minerals a comprehensive account of its stratigraphy and structure has not yet been made. A few small pieces of detailed work have been done, notably that on the fish faunas, but little is known beyond the brief summary given by David (1950). On the present survey only a few days were spent on the northern end of the outcrop.

The work which has been done shows that there are two main divisions, a lower consisting of acid and some basaltic volcanic rocks with interbedded sandstones and mudstones yielding an Upper Devonian fish fauna, and an upper, consisting mainly of fine grained sediment without volcanic rocks, containing a Lower Carboniferous fish fauna. There appears to be a conformable passage from the lower to the upper division. At the northern end of the outcrop there is an extensive series of extrusive rocks, the Violet Town Volcanics, a series of dacites 1500 feet thick with one thin flow of rhyolite at the base. These volcanics have been assigned to the Middle Devonian by David (1950), but more recent work shows that they are Upper Devonian in age (White, 1954). The volcanic rocks are intruded by granites, the emplacement of which was associated with annular fractures and caldera subsidence.

Further south in the area between Mansfield and the headwaters of the Howqua and Delatite rivers there is, according to David, a thickness of 2,500 feet of beds resting on an eroded surface of porphyrites and granite which are probably of the same age as the Violet Town complex. These consist of conglomerates, followed by purplish-red grit and beds of red micaceous mudstone, conglomerate, coarse and fine massive sandstone and flaggy sandstone with shale and mudstone at the top. There are also interbedded flows of basalt and felsite. The typical Upper Devonian fishes Bothriolepis and Phylloopsis have been found in the lower part of the succession. In the Mansfield area there are at the top of the succession, according to David, "160 feet of chocolate to purplish mudstones with

micaceous and calcareous sandstones and green to bluish calcareous shales abounding in fish remains and other fossils." The fish remains prove conclusively a Lower Carboniferous age for these beds.

On the eastern side of the outcrop, 50 miles southeast of Mansfield, there is a section 5,800 feet thick which has been called the Snowy Bluff Series. At the base are conglomerates and coarse pebbly sandstones 800 feet thick, overlain by at least 1000 feet of felsite. The rest of the section is made up of alternating sandstones, shales, grits and quartzites with interbedded basalt flows and one flow of felsite. A red colour predominates among the sediments.

In the southern part of this belt of Upper Devonian-Lower Carboniferous outcrops the total thickness is thought to be much more than at the places mentioned above; the Lower Carboniferous beds, in particular, become much thicker. However a detailed account of these sections has not yet been published. At Taberabbera, near the southern end of the outcrop, sub-horizontal beds of Upper Devonian age rest unconformably on steeply dipping Middle Devonian beds. This is the classical section illustrating the Taberabberan orogeny. To the west of the main outcrop there are several outliers of Upper Devonian rocks, mainly acid volcanics, which extend as far as Mount Macedon, northwest of Melbourne.

Correlation

A study of the fossil fish shows that the lower division, with its volcanic rocks, is Upper Devonian in age. Preliminary work on the Wuttagoona fish fauna indicates that it is also Upper Devonian but younger than that of the Mansfield area. It appears that the Upper Devonian part of the Mansfield succession can be correlated with the Mulga Downs Beds and perhaps the Belford Beds of the Cobar area. There is no evidence of any beds of the same age as the Amphitheatre Beds and it seems probable that there was no deposition in the Mansfield area at the time of deposition of most or all of the Amphitheatre Beds.

The Mansfield-Mitchell River outcrop is important as it is the only one with sediments which can be proved by fossil content to be of Lower Carboniferous age. Since no evidence has been found of an unconformity between the Upper Devonian and the Lower Carboniferous sediments, it is possible that the upper parts of the same series of beds cropping out around the Murray Basin range in age up to the Lower Carboniferous. It is for this reason that the term Upper Devonian-Lower Carboniferous Beds has been used throughout this report. Another possibility, however, which should be remembered is that the dominantly fine grained sediments with the Carboniferous fish at the top of the Mansfield succession may be younger than any of the sandstones at the top of the succession in the other outcrops round the Murray Basin, and that the beds described in these places as Upper Devonian-Lower Carboniferous may not in fact range in age beyond the Upper Devonian.

Structure

The northern part of the outcrop is bounded on both sides by powerful faults with direction of approximately N 35°W. The structure is in general that of a shallow syncline and dips are low except along the two boundary faults. Further south there are gentle folds with northwesterly axes. This structure is similar to that of the Lachlan-Narrandera area, but the deformation appears to be more moderate.

GRAMPIANS AREA

There are extensive outcrops of Upper Devonian-Lower Carboniferous sediments in western Victoria forming a series of rugged hill ranges extending from the Grampian Range to the Serra and Victoria Ranges in the south, a distance of 50 miles. The same beds reappear from beneath the alluvial cover further west in the Black Range and in several smaller outcrops to the north and south. To the southwest of the Black Range there are many small outcrops of acid volcanic rocks which are at the base of the Upper Devonian sediments. Very little work has been published describing these outcrops in western Victoria. David (1950) assigned the sediments to the Lower Carboniferous on the basis of some poor fossil evidence and gave the thickness as more than 2,000 feet. Recently Mr. Spencer-Jones, of the Victorian Mines Department, has been engaged in a detailed survey of the area and although the results have not yet been published, much useful information has been derived from discussions. A preliminary estimate by Mr. Spencer-Jones of a section west of Hall's Gap is given in Table 9. On the present survey by the writer only the northern part of the outcrop was studied and a section of almost 15,000 feet, mainly of sandstone and conglomeratic sandstones was measured on a traverse over Mount Difficult to Lake Wartook on the western limb of the syncline into which the beds are folded. (Plate 5). The section is given in Table 10.

The two sections are of almost the same beds which can be traced around the northern nose of the syncline and down its eastern limb, only slightly offset by faulting. However the Mount Difficult section includes some higher beds not in the Hall's Gap section, and the latter includes lower beds not in the Mount Difficult section. Although the Mount Difficult section was not studied in enough detail to enable each formation to be correlated, the same threefold division is evident in both sections, a lower coarse division, a middle one of medium and fine sandstones with some mudstones, and an upper coarse division. The middle division thins from 5,100 feet at the Mount Difficult section to 4,000 feet at Hall's Gap, a thinning which Spencer-Jones has shown to continue to the south. It appears therefore that the lowest division must be at least as thick at the Mount Difficult section, as the 7,400 feet cropping out in the Hall's Gap section. This means that at the Mount Difficult section there is a total thickness of at least 17,500 feet.

Southward from Hall's Gap Spencer-Jones has found the outcrop of the lower formations on the eastern side of the outcrop wedging out in a way which suggests thinning of the formations rather than faulting. This thinning continues until near Mount Abrupt, 35 miles south of Hall's Gap, where the Mt. Rosea sandstone is in contact with Ordovician rocks and preliminary trenching by Spencer-Jones seems to show that the contact is unconformable. If this is so, it means that there must be a very abrupt thinning of the lower formations towards the south.

The volcanic rocks to the southwest, which are of rhyolitic and trachytic types, have been shown by Spencer-Jones to rest unconformably on the Cambrian and Ordovician and to underlie the Upper Devonian sediments. There are no outcrops of the lavas in the main Grampian-Serra Range outcrop and it appears that the lavas are not present there below the sediments, although this will not be certain until the unconformable nature of the contact at Mount Abrupt is proved conclusively. The relationship in time between the lavas and the lower sediments in the Grampians is not clear, that is whether the lavas were contemporaneous with the lower beds or older than all the sediments, but it is probable that the latter is true. The

TABLE 9.

SECTION OF UPPER DEVONIAN-LOWER CARBONIFEROUSROCKS WEST OF HALLS GAP

(after D.Spencer-Jones)

From the top

Formation	Thickness	Lithology
<u>VIII</u> Mount Rosea	1,500 +	Massive sandstone.
<u>VII</u> Silverband	2,000	d. Thin bedded, sun cracked shale with <u>Lingula</u> , fish spines and ostracods. c. Sandstone. b. Thin purple and red sandstone shale and hard sandstone and quartzite. a. Soft and hard, thin, slabby sandstone.
<u>VI</u>	2,000	Slabby hard, red and yellow sandstone.
<u>V</u>	1,900	Hard, slabby and massive, cross-bedded sandstone.
<u>IV</u>	700	Soft, red sandstone and shale with hard, slabby sandstone.
<u>III</u>	2,000	Hard, massive, slabby, cross-bedded sandstone.
<u>II</u>	500	Thin, soft, red and purple sandstone and shales.
<u>I</u>	2,300	Hard, cross-bedded sandstone.

TABLE IOUPPER DEVONIAN - LOWER CARBONIFEROUS BEDSAT THE END OF THE GRAMPIAN RANGE

(From the top)

<u>Division</u>	<u>Thickness (feet)</u>	<u>Lithology</u>
<u>Upper</u>		
<u>V</u>	3,000	Very massive, pale grey, coarse sandstone with scattered small quartz pebbled in some beds.
<u>IV</u>	1,200	White, false bedded medium and some fine sandstones.
<u>III</u>	800	Coarse, buff sandstone with scattered small pebbles in some beds.
<u>II</u> B	3,100	Rather soft, whitish, buff and red, medium and fine sandstone. Some ripple marking.
<u>II</u> A	2,000	Well bedded, massive, pale grey buff and some red, medium grained sandstone. A thin bed of soft, dark red, muddy siltstone at the top.
<u>I</u>	4,700 +	Pale grey, massive, strongly false bedded, very coarse, conglomerate sandstones containing small angular quartz pebbles.
Total:	<u>14,800</u>	

contact between the lavas and the sediments has been seen at only one place by Spencer-Jones in a small outlier at Wickcliffe, south of the main outcrop, where there is a small thickness of interbedded sandstone and lava. Apart from this one place neither lavas nor ashes has been found interbedded in the lower part of the sandstones.

Correlation

The correlation of the sediments with the Upper Devonian-Lower Carboniferous beds to the north and east on grounds of lithology and structure seems certain although conclusive palaeontological evidence has not yet been found. Previously the little fossil evidence that was available was taken to indicate a Lower Carboniferous age. This evidence is very far from being conclusive. The Lingula found near the top of the Silverband Formation was thought by Chapman to be Lower Carboniferous because of a supposed similarity with L. squamiformis of the European Lower Carboniferous (Chapman, 1917). Some of the fish remains were determined as Physonemus, which was taken to indicate a Carboniferous age; but Prof. Sherbon Hills has informed the writer that too much weight should not be given to this evidence. Perhaps the ostracods found by Spencer-Jones will prove more useful.

The acid volcanics were presumably extruded in the same volcanic episode as the similar lavas in eastern Victoria and New South Wales. The overlying sediments are the same, in their main features, as those in the west of New South Wales. The sandstones consist of almost pure silica. The pebbles are almost all of vein quartz; they range in size up to two inches in diameter but are seldom more than one inch. There are no coarse pebble beds like those in the Cobar and Mootwingee areas. Most of the sandstones are pale in colour, whitish, grey, and buff, but there is also a considerable amount of red colouration. The sediments in this area are intermediate in colouration between the pale sediments of the Mootwingee and Cobar area and the red sediments of the Mansfield area, similar in colouration to the sediments of the Narrandera-Cocparra section.

No obvious lithological correlation presents itself between the sedimentary units of the Grampian section and those in New South Wales. However for the present a tentative correlation is suggested between the finer middle division and the Lingula Beds of the Mootwingee Section and the Amphitheatre Beds. This division is similar to the Lingula Beds in consisting mainly of well sorted medium and fine sandstones with subordinate amounts of mudstone. However it differs in lacking the abundant animal tracks and burrows of the Lingula Beds and in containing less interbedded mudstone. A palaeontological report with a comparison of the Lingulas of the two places has not yet been received. If the correlation suggested is correct there are no beds in the Mootwingee section equivalent to the thick, coarse sandstones at the base of the Grampian section. The coarse beds forming the upper division of the Grampian section are probably of the same age as the Mulga Downs Beds and the Ravendale Beds. The writer saw no finer sandstones at the top of the Grampian section which might be correlated with the Ravendale Beds and the Belford Beds, but Spencer-Jones mentioned seeing fine sandstones at the southwestern part of the main outcrop which appear to be the youngest beds in the section.

Structure

At the northern end of the Grampian Range the structure is that of an asymmetrical syncline, faulted on the steeper eastern side against Cambrian and Ordovician rocks, with a N.N.W.-S.S.E. axis parallel to the eastern boundary fault. Further south the axis turns

to a southerly direction, diverging from the fault, and at the northern end of Lake Wartook it turns gradually to a south-south-westerly direction. The dip of the western limb of the syncline increases from 30° in the north to 40° at Lake Wartook. On the eastern limb the dip steepens near the boundary fault and the bedding is vertical along much of the escarpment on the eastern side of the hills. At a few places the beds appear to be tilted beyond vertical, suggesting that the eastern boundary of the outcrop is a reverse fault, an arrangement similar to that of the reverse Cobar Fault on the eastern boundary of the Upper Devonian-Lower Carboniferous rocks of that area.

There are no large faults cutting the rocks in the Grampians Range, and relatively few small faults in the northern part of the fold. South of Lake Wartook there are numerous small faults with an average direction of roughly northwest. Throughout the whole of the outcrop the massive beds are cut by a strongly developed system of joints.

In the Black Range to the west the regional dip is to the west, suggesting that to the west of the Grampian syncline is an anticline most of which is now covered by alluvium.

Igneous intrusions

There are three fairly large granitic intrusions into the sediments in the Grampians-Serra Range outcrop and several smaller intrusive masses. The most northerly of the larger intrusions, the only one which was mapped by the writer, is a roughly circular stock of pale grey, coarse, granodiorite with a diameter of about five miles, to the west of Lake Wartook. There is little alteration of the sediments beyond a narrow aureole of contact metamorphism in which there is silicification and some feldspathisation and tourmaline veining. Some gold mineralisation is associated with these granites, mainly the larger intrusions in the south where mining was fairly important at one time. To the south and east of the granite at Lake Wartook are several intrusions of pink feldspar porphyrite which are irregular in form, passing from dykes into concordant intrusions. It is probable that these minor intrusions are part of the same igneous episode as the granodiorite.

SUMMARY OF STRATIGRAPHY AND STRUCTURE

1. Form of the basin

The details of thickness, lithology and structure of the sediments, which are given above, prove the existence in the Upper Devonian of a deep basin between the Australian shield on the west and a rapidly rising geanticline in the east (Plate 6). The greatest thickness of sediment, 21,000 feet, was measured west of Cobar and it is probable that the greatest thickness in the basin is not much more than this. At the Mootwingee section to the west the total thickness is at least 18,300 feet and the areas of greatest thickness probably lie between these two points, nearer to the Cobar area, as basins of the type are usually asymmetrical, being steeper on the side nearer the geosyncline.

On the eastern side of the basin, in eastern New South Wales, there was a belt of intense volcanic activity along which acidic and later some basaltic lavas several thousand feet thick were poured out. Although the eastern limit of the igneous activity lies beyond the present coast line, the change in thickness and lithology of the sediments in the northeastern corner of New South Wales shows that they were deposited on the eastern flank of the geanticline in a

more marine environment than those in the trough on the western side. Not one pebble of the Upper Devonian volcanics was found in the sediments in the middle of the basin, and this fact, together with that of the presence of numerous Silurian pebbles, suggests that the source of sediments was an uplifted belt following the present Silurian outcrops close to the deeper eastern side of the basin. This rising geanticline appears to have been distinct from the volcanic belt and to have excluded volcanic deposits from being carried westwards into the basin.

Further south in Victoria the volcanic belt swings around to an east-west direction continuing almost as far west as the South ^{also} Australian border. This is the first appearance in this part of the Tasman geosyncline of an east-west uplift. ^(KAMMOTO TROUGH N.E.-S.W.) The eastern part of the volcanic belt coincided approximately with a geanticline which had been in existence at least since the Benambran orogeny at the beginning of the Silurian. But in the Silurian and older rocks there is no trace of any transverse structures in the geosyncline. This east-west zone of uplift, which first appeared in the Taberabberan orogeny, has persisted with varying importance to the present day when it forms the Dividing Range between the Murray Basin and the sea. ^{Mapping required}

To the south of the deepest part of the basin there is an abrupt thinning of the sediments on what appears to be a platform between the basin and the east-west volcanic belt. The thickness of the Ardlethan-Cocoparra section is 8,000 feet, compared with the 21,000 feet west of Cobar. Most of the thinning appears to take place along an important structural line following the course of the Lachlan River which has been called the Lachlan Line and which forms the boundary between the platform and the deep basin to the north. At the western edge of the platform the thick section in the Grampian Range suggests that there was a separate small deep basin or an extension of the main basin between the platform and a northerly projection of the western end of the volcanic belt. However there is not enough evidence of changes of thickness and facies to define the limits of this sub-basin.

The western limit of deposition is not known as sediments which overlapped on to the shield have all been removed. However the thickness of the sediments at the most westerly outcrops, 18,000 feet at Mootwingee and 17,000 at the Grampian Range, shows that the edge of the basin must have been further west. The coarseness of the sandstones and conglomerates in the Mootwingee beds makes it clear that the source of the sediments to the west was an area of high relief, mountains composed of folded Proterozoic and Cambrian rocks. ^{possibly ?}

The northward continuation of the basin disappears under the Mesozoic sediments of the Great Artesian Basin. The question of the extent of this northward continuation of the basin is discussed later.

2. Sedimentation

Sedimentation in this basin was in four clearly defined phases separated by earth movements which caused unconformities separating the highest three.

1. In the earliest stages the sinking of the basin was slow and the basin formed a shallow arm of the sea, open to the north and northeast, in which well sorted shelf deposits were laid down. In the middle of the basin, in the Cobar area, there were clear shallow seas in which sandstones with an abundant fauna of brachiopods, lamellibranchs and crinoids were deposited. To the west the conditions become less marine and the only fossils are numerous animal tracks and burrows and a few linguloids. The greatest thickness of these sandstones, the Lower Amphitheatre Beds, is more than 3,100 feet in the

-Cobar area. The fauna is clearly Upper Devonian, but sufficiently detailed work has not yet been done to make possible more precise dating.

2. In the second phase of sedimentation the rate of sinking of the basin was greatly accelerated till it outpaced deposition, resulting in a deep basin with steep slopes which in the unstable conditions caused repeated slumping and turbidity currents. The sediments deposited in these conditions are an unsorted mixture of sand, silt and mud with a green colour in which graded bedding is the rule and slump structures are common. In the deep muddy waters life was almost impossible and the sediments are barren of organic remains. The greatest thickness of these flysch deposits, the Upper Amphitheatre Beds, which has been measured, is the 4,500 feet in the Cobar area.

To the west the sediments are thinner and red sediments are interbedded with the green. In the Mootwingee area conditions were more suitable for life and linguloids flourished from time to time.

3. The second phase of sedimentation was ended by strong earth movements which probably caused an unconformity throughout the whole of the basin. Rapid uplift of the mountain ranges to east and west resulted in a sudden increase in the coarseness of the sediments reaching the basin. The sediments consist of sandstones and conglomerates with very small amounts of silty mudstones. Strong cross-bedding is present in almost all of the sediments and ripple marks are common. The colour of the sandstones in the central and western part of the basin is whitish or pale grey whereas in the south and south-east a red colouration becomes progressively stronger as the volcanic belt is approached. These sediments were deposited by strong streams from the mountains as outwash fans and in freshwater lakes. The greatest thickness which has been measured is the 9,700 feet of the Mootwingee Beds on the western side of the basin, compared with only 7,000 feet of Mulga Downs Beds in the Belford section which is nearer the middle of the basin.

The only fossils found in these beds, apart from some animal tracks in the Mootwingee area, are the fossil fish from Wuttagoona which are near the base of the Mulga Downs Beds. Preliminary work on this material by Prof. Sherbon Hills and Mr. H. Fletcher has shown that the fauna is high in the Upper Devonian and therefore on the present evidence it seems probable that the whole of the Mulga Downs Beds, a rapidly deposited formation, is of Upper Devonian age.

4. After the deposition of the Mulga Downs Beds and Mootwingee Beds there were strong earth movements which caused a strong angular unconformity in the West Darling District and probably also caused unconformity in the middle of the Basin. The succeeding sediments, the Belford Beds and the Ravensdale Beds, are finer than the underlying beds, and consist of medium and fine white sandstones with only a few scattered pebbles. They are softer and less firmly cemented than the underlying coarse beds. Well rounded and polished grains in some beds show the importance of aeolian action. No interbedded mudstone was seen. These sandstones were deposited in a terrestrial environment in an arid climate, with aeolian erosion and perhaps deposition taking an important part. The maximum known thickness is the 5,800 feet of the Belford Beds in the Belford section.

In the absence of fossils, all that can be said with certainty of the age of these beds is that they are younger than the high Upper Devonian fish fauna at Wuttagoona and older than the Permian. It is possible that they may be Lower Carboniferous in age,

approximately contemporaneous with the fish-bearing mudstones of the Mansfield area. There is a conformable passage from Devonian to Carboniferous in eastern New South Wales. However it is quite possible that there are no sediments in the main part of the basin of the same age as the Mansfield Lower Carboniferous mudstones and that the Belford and Ravensdale Beds do not range in age beyond the Upper Devonian. Very little is known about the Upper Devonian-Lower Carboniferous rocks of the Mansfield-Mitchell River outcrops and it is possible that further work will show that the Lower Carboniferous rocks were deposited in a separate basin. A correlation diagram of the Upper Devonian-Lower Carboniferous rocks in Victoria and New South Wales is given in Figure I.

3. Deformation of the basin

The period of the formation and development of the basin was one of instability and no doubt there were frequent movements of varying importance. However the evidence of the sediments shows that there were three main periods of compression and uplift, the last of which closed the history of the basin,

1. In the Cobar area it appears that at least 1,500 feet of sandstones at the top of the Amphitheatre Beds were removed by erosion from the Belford area before the deposition of the Mulga Downs Beds. This indicates fairly strong uplift after the deposition of the Amphitheatre Beds. The greater intensity of folding in the Amphitheatre Beds at outcrop compared with the Mulga Downs Beds, while due mainly to the general westerly decrease in intensity of folding, might be due to some extent to folding in this period. It is to be expected that this strong unconformity near the middle of the basin would also be present in the West Darling District, nearer the western edge of the basin. That this is the case is suggested by the absence of the Lingula Beds in the Coppermine Range, where the Mootwingee Beds appear to rest directly on the Proterozoic. The intensity of the earth movements at this period is shown by the great flood of coarse detritus which descended from the mountains bordering the basin following their uplift.

2. There was a second period of orogenic movement in the West Darling District after the deposition of the Mootwingee Beds. There was a large sinistral horizontal displacement along the north-northwesterly Koonenberry Fault and parallel faults to the west with related dome and basin structures. The faulted slices were elevated to varying heights, and from the highest, all the Lingula Beds and Mootwingee Beds were removed before the deposition of the Ravensdale Beds. In this area the greater part of the deformation of the Lingula Beds and Mootwingee Beds took place at that time, and it is possible that some of the folding in beds of the same age further east took place at the same time, although the effects of these movements cannot be distinguished from those of the final orogeny which ended the life of the basin.

3. In the final orogeny the sediments were thrown into folds with a fairly uniform N.N.W.-S.S.E. direction. The strongest folding is on the eastern side of the deepest part of the basin near Cobar, and it increases rapidly in intensity near the reverse fault which forms the eastern boundary of the outcrop and which might also be approximately on the position of the eastern boundary of the deepest part of the basin. In the area south of the Lachlan Line, where the sediments are thinner, the folding was gentler, with the limbs of most of the folds dipping at 15° and less. The thicker sediments

in the Grampians area are folded into a slightly steeper syncline bounded on the east by a reverse fault in a manner similar to that at the faulted eastern boundary at Cobar.

Between the parallel Darling and Lachlan Lines there is a zone in which structures with a northeast to southwest direction are prominent. In this zone is a third parallel line, the Neckarbo Line, along which the sediments have very steep dips and are sheared and contorted. There are several small tight folds which vary in direction from parallel to the shear zone to an east-west direction. The Neckarbo Line is interpreted as a line of shearing with a horizontal displacement. It is probable that similar horizontal displacements took place along the other two main lines in this zone, the Darling and Lachlan Lines, and that the three form a set of N.E.-S.E. lines of horizontal displacement separating blocks to the north and to the south with a dominantly north-northwesterly strike. Evidence relating to the sense of the displacement on these lines appears to be contradictory. The direction of divergence of the folds from the Neckarbo Line seems to indicate a sinistral displacement, but other evidence suggests a dextral displacement. The latter is thought to be the more likely. However a detailed discussion of the evidence and its implications is beyond the scope of this report.

The age of these latest orogenic movements cannot be determined exactly because of the lack of evidence from fossiliferous sediments in the basin. In other areas where there is better evidence it can be shown that there was an epoch of strong orogenic movements at the end of the Lower Carboniferous, the Kanimblan orogeny, and it was probably in this orogeny that the last folding of the Upper Devonian-Lower Carboniferous Beds in the marginal trough took place. It was probably also in the Kanimblan orogeny that the granites and porphyries of the Grampian area were intruded.

CONTINUATION UNDER YOUNGER SEDIMENTS

A fairly good estimate can be made of the extent, thickness and structure of the Upper Devonian-Lower Carboniferous rocks under Tertiary cover in the Murray Basin by the projection of the main features of structure and facies outlined above, helped by some evidence from boreholes and geophysical work. On the southeastern side of the Lachlan Line the sediments are thin, not more than 8,000 feet, and the lower marine beds, the Amphitheatre Beds, are absent or very thin. The sediments are in a series of gentle folds with north-northwesterly axes. Throughout much of this structurally high area, probably most of it, these sediments have been removed entirely, and the Tertiary beds rest directly on Ordovician or Silurian rock. Several boreholes near Lake Tyrrel intersected slates, probably of Ordovician age, underlying the Tertiary.

On the northwestern side of the Lachlan Line the sediments thicken rapidly and in the deepest part of the basin reach a thickness of more than 20,000 feet. A strong negative gravity anomaly with a northeasterly elongation at the junction of the Lachlan and Murray Rivers is probably caused by a thick series of Upper Devonian sandstones on the northwestern side of the Lachlan Line with metamorphosed Ordovician rocks on the southeastern side. At the western side of this negative anomaly a sharp increase in gravity along a straight line with a direction slightly east of north appears to be caused by a fault, which has been named the Lake Tyrrel Fault, bringing Devonian sandstones on the west down against Ordovician rocks.

It is probable that the Upper Devonian-Lower Carboniferous sediments were originally deposited far to the west of the present

outcrops and that the sediments in the middle of what is now the Murray Basin were fairly thick. However borehole evidence indicates that the sediments have been removed from much of this area before the deposition of the Tertiary. A line of five boreholes stretching southeastwards from Menindee on the Darling River to the Arumpo Bore all found below the Tertiary what were called 'blue slate', 'blue slate with quartzite veins' and 'grey rock'. Detailed descriptions or samples of these rocks are not available, but it seems very probable that they are older than the Upper Devonian, perhaps Proterozoic or Ordovician. The abrupt ending of the thick Upper Devonian-Lower Carboniferous sediments seems to be caused by a fault nearly on the same line as the powerful Koonenberry fault to the north, but offset a short distance to the west on crossing into the zone of northeasterly faults.

It appears, therefore, that this fault and the Lake Tyrrel fault form the western boundary of the main mass of the Upper Devonian-Lower Carboniferous sediments. However, there is some evidence of patches remaining to the west of these faults. There is a long narrow negative gravity anomaly with a northeasterly elongation in northwestern Victoria approximately on a continuation of the Neckarbo Line and the ridge of steeply dipping Mulga Downs Beds and Belford Beds which form the Manara Range. The most probable interpretation of this anomaly is that it is formed by a slice of steeply dipping Upper Devonian sandstones along a shear zone, faulted on both sides against older, denser rocks, in the same way as the faulted slice of Koonenberry Mountain. Other similar narrow slices of these sandstones may be present. The Bungunnia borehole in the northwestern corner of the basin found 400 feet of sandstone, underlying the Tertiary and overlying red slates, which Dr. Ludbrook of the South Australian Mines Department thinks is not Cretaceous and is younger than Proterozoic (personal communication). There is also white sandstone below the Tertiary in the Canopus No. 2 Bore. The sandstone in both these bores might be Upper Devonian.

The evidence presented in this report suggests strongly that thick Upper Devonian-Lower Carboniferous sediments extend northwards under the Great Artesian Basin, a possibility which has usually been dismissed in the past largely, no doubt, because of the very low published estimates of thickness in the New South Wales sections. The small outcrops of granite near Hungerford on the Queensland border appear to be on a continuation of the uplifted belt of Silurian rocks intruded by granites which are on the eastern edge of the Upper Devonian basin in New South Wales. Between the Hungerford granite outcrops and the Proterozoic outcrops in the Koonenberry and Tiboburra areas to the west there is enough room for the basin to continue to the north-northwest with undiminished width, and it seems probable that it does so. Evidence in support of this suggestion is provided by the presence in the Cretaceous beds near White Cliffs of boulders of fossiliferous quartzite from the Lower Amphitheatre Beds. Sediment of this type is not present at the outcrops to the west and the boulders must have been derived in the Cretaceous from outcrops now covered by Cretaceous sediments.

It is possible that about the Queensland border the basin might swing to a north-northeasterly direction and join up with the Drummond Basin. The Drummond, Star and Hodgkinson Basins, a line of Upper Devonian basins extending for 700 miles in central and north Queensland, are very similar to the marginal trough in New South Wales. This line extends in a north-northwesterly direction parallel to the New South Wales basin but with its southern end offset to the east. The Anakie High extends along its eastern margin and at the southern end of the Drummond Basin it seems to turn to a N.N.E.-S.S.W. direction to join the Nebine Ridge which continues as far as the granite ridge at Hungerford. It is suggested that an Upper Devonian trough might continue on the western side of the Nebine Ridge between the Drummond Basin and New South Wales trough.

UPPER CARBONIFEROUS-PERMIAN

After the Kanimblan Orogeny at the end of the Lower Carboniferous the main basins of deposition were restricted to an area near the present east coast and the region of the Murray Basin remained a continental area subjected to erosion and eventually peneplanation until the Lower Cretaceous. The region uplifted by the Kanimblan orogeny was covered by an ice sheet in the Upper Carboniferous and the glaciation persisted into the Lower Permian. Of the glacial sediments which must have been originally widespread there are only small patches scattered along the southern margin of the Murray Basin in Victoria and South Australia. These patches, which consist of tillites, varved shales and outwash sandstones and gravels, are preserved in downfaulted blocks which in Victoria usually trend in a N.N.W.-S.S.E. direction. The glacial sediments are unfolded and have low dips except near the larger faults. Some of the faults in central Victoria have been shown to be steep reverse faults, probably formed by the rejuvenation of the reverse faults common in the Lower Palaeozoic rocks.

The only Upper Permian sediments in the Murray Basin region are in a small patch at Coorabin in the southeastern corner of the basin on the north side of the Murray River, where beds of the upper coal measures underlying thin Tertiary and Quaternary sediments were found accidentally and are now worked for coal. Recent geophysical work has shown that the Permian beds have an area of at least 600 square miles and a maximum depth of 1,500-2,000 feet (Thyer and Vale, 1952). Boreholes show that the beds are gently folded, but there is little evidence of the form of the folds.

Boreholes on the southern edge of the Murray Basin have found small areas of Permian glacial beds under the Tertiary in both Victoria and South Australia and it is possible that similar patches might be present elsewhere in the basin. There is no record of any Upper Permian beds other than those of Coorabin being found in the basin. Because of the absence of evidence relating to the form of the Upper Permian basin and the extent of subsequent faulting of its sediments little can be said about the possibility of other areas of Upper Permian sediments being present under the Murray Basin; but the possibility cannot be ignored.

MESOZOIC

Evidence that Mesozoic sediments are present in the Murray Basin has appeared only recently, although there had been in the past some speculation as to whether the Cretaceous sediments continued southwards from the Great Artesian Basin beyond their most southerly outcrop at Wilcannia, on the edge of the Murray Basin. A borehole drilled by an oil exploration company at Loxton in 1956 found below the Tertiary sediments rocks with a marine Cretaceous microfauna. A re-examination of samples from the bottom of an older deep bore, the Company's bore, a few miles to the northeast, revealed again Cretaceous fossils. Apart from a shallow borehole near the northern margin of the basin these two boreholes provide the only direct evidence of Mesozoic sediments in the basin. However a study of stratigraphy and structure in and around the basin combined with the little information from boreholes enables some inferences to be made concerning the extent of the Mesozoic sediments in the basin and their thickness.

GREAT ARTESIAN BASIN

The stratigraphic succession of the Mesozoic beds is well known in the Great Artesian Basin, because of the large number of water bores, and it may be used as a type section. In the development of the Great Artesian Basin there were two main transgressions, the first in the middle Trias (Bundamba Sandstone), and the second in the Lower Aptian (Blythesdale Group). Of these only the second reached the edges of the Murray Basin and, as it seems unlikely that any pre-Blythesdale sediments are present in the Murray Basin, a description of only the Blythesdale Group and younger beds will be given. The Cretaceous succession is as follows:

Rolling Downs	{	Winton Formation
Group		Tambo Formation
		Roma Formation

Blythesdale Group

The lower beds in the Blythesdale Group contain no marine fossils and may range in age back to the uppermost Jurassic. The main transgression took place with the upper beds and it was probably those which reached the edge of the basin. They contain marine fossils in some places which prove a lower Aptian age. The Blythesdale Group attains a thickness of more than 1,000 feet in the eastern part of the basin near Roma, but is probably represented in the south-western corner by the 150 feet of grits, conglomerates and medium grained sandstones at the base of the Mesozoic beds in the Tibooburra area. Kenny (1934) dated these beds as Jurassic but a correlation with the Blythesdale Group is more likely.

The overlying Rolling Downs Group is dominantly argillaceous, consisting mainly of blue mudstones and shales with concretionary limestones, sandstones and, in the Winton Formation, some thin coal seams. The Roma Formation contains an abundant marine fauna of Aptian age. The Tambo Formation, which is separated from the Roma Formation by a non-sequence, contains a fauna of Upper Albian age which, although mostly marine, indicates shallow water conditions very close to land. It includes ichthyosaurs, plesiosaurs, dinosaurs and turtles. There is a gradual transition to the Winton Formation, a freshwater deposit which differs from the underlying beds only in the absence of marine fossils, the higher proportion of sandstone and the presence of a few thin coal seams. The age will not be certain until the flora is described, but it is probably early Upper Cretaceous, Cenomanian and later (Whitehouse, 1954).

The Cretaceous sediments thin gradually southwards on to a bedrock ridge extending from the Broken Hill massif in a south-southeasterly direction to Cobar. From the Broken Hill massif a bedrock ridge extends northwards as far as Tibooburra and on the eastern side of this there is a fairly deep lobe of the basin which extends to the low saddle in the Broken Hill-Cobar ridge. A borehole in this lobe at an undefined locality at Momba Station approximately 20 miles east of White Cliffs, penetrated 2,000 feet of Cretaceous sediments without reaching the bottom (Pittman, 1895, p.111). In the highest beds at White Cliffs, in which the opals are found, the writer collected a microfauna identified by Dr. Ludbrook as belonging to the Tambo Formation. The spoil heap of a shaft which began at a horizon not more than 50 feet below the fossiliferous Tambo beds, and which is reputed to be about 100 feet deep, contained pieces of grey, glauconitic, sandy shale in which Dr. Ludbrook identified an Aptian (Roma) microfauna. It appears, therefore, that near White Cliffs there are nearly 2,000 feet of sediment of Roma age and older.

BROKEN HILL-COBAR RIDGE

A small patch of decomposed kaolinitic sandy shale of Cretaceous age was found in the middle of the Broken Hill-Cobar Ridge beside the Wilcannia road, 40 miles from Cobar. In channel samples of six feet of this sediment Dr. Ludbrook identified a small microfauna of Tambo age. Further west on the plains bordering the Darling River there are some small exposures of weathered blue clays which yielded no fossils, but which are similar in lithology to the Cretaceous clays. Many boreholes on the south bank of the Darling River and the northern flank of the Broken Hill-Cobar ridge penetrated grey clays and white sandstones (Harper, 1934, p.75) which are usually thought to be Tertiary or Quaternary but which might be Cretaceous. There is a possibility of a further extension of the Cretaceous outcrops on to the southern flank of the Broken Hill-Cobar ridge. Mulholland (1940) described a series of 'blue clays and white sands' mainly from boreholes which have a fairly wide outcrop southwest of Cobar. He thought they were Tertiary, but a Cretaceous age now appears possible because of the lithology and because the discovery of the small outcrop west of Cobar shows that the Cretaceous sea did reach as far as the top of the Broken Hill-Cobar ridge. This outcrop is shown as doubtful Cretaceous on the map.

THALLON (MARANOA) BASIN

The Thallon Basin is a southerly extension from the southeastern corner of the Great Artesian Basin separating the Broken Hill-Cobar ridge from the mountains of the Dividing Range. It is on a northeasterly continuation of the Darling-Lachlan belt of northeasterly structures and is bounded on its southeastern side by a continuation of the Lachlan Line which has been described in connection with Upper Devonian structures. Recent borehole evidence has shown that movements along this N.E.-S.W. belt continued in the Mesozoic resulting in some deep, narrow troughs in the basin with N.E.-S.W. elongation and some N.E.-S.W. faults in the Mesozoic beds (Rade, 1953, 1954, 1954A). In the deeper basins the Mesozoic beds attain a thickness of slightly over 3,000 feet. The lowest beds are the equivalents of the Jurassic Walloon coal measures consisting of sandstones and black pyritic shales showing cyclic sedimentation, with some conglomerate near the basement ridges. The maximum thickness is 800 feet. The Blythesdale Group, which has a maximum thickness of 600 feet, is a lacustrine deposit consisting of shales and sandy shales with coal seams and sandstone intercalations. The average thickness is 600 feet. Above the Blythesdale Group are marine beds, blue and green shales, which Rade calls Roma Formation, but which might also include the Tambo Formation as the Tambo Formation is not mentioned by Rade. The thickness is 700-900 feet. The overlying Winton Formation, which has an average thickness of 500 feet, consists of lacustrine deposits, sandy clays with occasional seams of lignite.

WESTERN VICTORIA

In western Victoria around Casterton and the valley of the Glenelg River a group of freshwater sediments of Mesozoic age, the Merino Group, rest on Palaeozoic metamorphic rocks and granite. They are on the top of the 'high' in the sub-Mesozoic surface on the southern side of the Murray Basin, and they continue southwards under Tertiary beds into the deeper basin along the coast of Victoria and South Australia. In the Casterton area the group consists of at least 1,000 feet of interbedded mudstones and medium to fine grained feldspathic sandstone. The whole group used to be included in the Jurassic, on rather poor palaeontological evidence, but recently the uppermost 65 feet of the Merino Group in a cliff section

on the banks of the Glenelg River were dated as Cretaceous on the evidence of some dicotyledonous leaves (Kenley 1954). These upper beds, the Runnymede Formation, consist of friable, pale grey, feldspathic, fine grained sandstone and blue-grey mudstones and siltstones. They appear to be separated by a disconformity from the lower part of the Merino Group, which Kenley has retained in the Jurassic. However there has recently been a suggestion that the whole of the Merino Group might be Cretaceous.

MURRAY BASIN

Mesozoic sediments have been found in the Murray Basin only in boreholes. An outcrop of white sandstones and clays with some common opal in the southeastern part of the basin at Bidura was thought by Pittman (1895, p.108) to be of Cretaceous age. However the similarity in lithology with some of the Cretaceous beds on the southern edge of the Great Artesian Basin appears to be due to the similarity in the intense chemical weathering. A borehole drilled later at Bidura encountered black clays which are probably of Tertiary or Quaternary age.

Cretaceous sediments were first identified by Dr. Ludbrook in samples from the Loxton Bore in South Australia. The beds from 1,350 feet to the bottom of the hole at 1,601 feet are Cretaceous. The uppermost 237 feet, from 1,350 to 1,587 feet, consist of dark green, glauconitic clays and mudstones containing a Cretaceous microflora but devoid of marine fossils. The lower 14 feet consist of dark greenish-grey, carbonaceous shale with abundant glauconite and pyrite and containing Cretaceous marine foraminifera. There are not enough species to decide whether the age is Roma or Tambo, but the absence of the dominant Roma species in the small fauna does tend to favour correlation with the Tambo Formation. Core recovery from the marine beds was very low, but the cuttings and small pieces of core which were recovered were interpreted as showing boulders of bedrock, probably of the Kanmantoo Series (Cambrian), in the sediments. This question is discussed later. The re-examination of a few samples from the Company's bore, drilled in 1910, showed that the lowest 209 feet, from 1,596 feet to the bottom at 1,805 feet, consist of blue shale and sandstone containing a Cretaceous microflora, but no marine fossils. The only other record of Mesozoic beds in the Murray Basin is from a shallow borehole southeast of Menindee, near the northern margin of the basin, in which the Government Geologist correlated with the Cretaceous, 40 feet of beds between the Tertiary and the Precambrian bedrock.

STRUCTURE

The main part of the Great Artesian Basin (the Thomson sub-basin) is a gentle sag in the flat surface cut in Precambrian and Palaeozoic rocks filled with Mesozoic sediments with a maximum thickness of 6,000-7,000 feet. Throughout most of the basin the beds have a very low dip towards the middle of the basin, but there is some interruption of this uniform dip in the northeastern corner of South Australia where some gentle folds have recently been mapped. There is one similar broad anticline in the southern edge of the basin at Tibbooburra, which brings Precambrian bedrock to the surface, with a northeasterly axis pitching to the northeast. The silicified Tertiary Eyrian Formation is also folded, showing that some, at least, of the folding took place in the Tertiary. The rock exposures in the Cretaceous outcrops are not good enough to show whether the folding is steeper in the Cretaceous rocks. A broad, very gentle anticlinal flexure, also with a N.E.-S.W. axis, can be seen in the silicified Tertiary capping of the Cretaceous rocks at White Cliffs.

This arch is four or five miles wide and the crestal area is raised very little, probably less than 100 feet. Some rejuvenation along the Koonenberry Fault is apparent west of Tibooburra (the Waratta Fault) and at Koonenberry Mountain, at both of which places the downthrow, probably not more than 100-200 feet, is to the northeast.

The structures in the Thallon Basin have been shown by borehole evidence to be steeper than in the main part of the Great Artesian Basin. Several faults have been proved in two sets parallel to the two main structural directions of the area, N.N.W. and N.E.-S.W. The same directions are apparent in the basement ridges. However in this area the dominant direction is N.E.-S.W. and indicates rejuvenation of movement along the N.E.-S.W. belt between the Darling and Lachlan lines described in the section on the Upper Devonian-Lower Carboniferous rocks.

Although there is no direct evidence of the structure of the Cretaceous rocks in the Murray Basin itself, some deductions can be drawn from the structure of the Tertiary rocks since it is a reasonable assumption that the same 'high' and 'low' areas will be found in the Cretaceous beds as in the Tertiary. The Tertiary structures are plotted on Plate 7. The two dominating features are the Murrayville Monocline, and the bedrock ridge which extends in a southwesterly direction into the basin from the Upper Devonian outcrops west of Cobar. Across the Murrayville Monocline the top of the Miocene Limestone has been displaced 200 feet at one place and it is possible that the displacement may be greater in the lower Tertiary beds and greater still in the Cretaceous.

EXTENT UNDER THE MURRAY BASIN

At its greatest extent the Cretaceous marine transgression must have spread very widely over the flat peneplain to which most of eastern Australia had been degraded. It is possible that it spread over most of the Murray Basin and that a thin layer of Cretaceous sediments was deposited over most of the basin. If this was the case, most of the sediment has been removed by pre-Tertiary erosion, although some small patches may exist undiscovered, perhaps indistinguishable from the innumerable small patches of decomposed and silicified Tertiary deposits on the peneplain surface. However the evidence from boreholes makes it clear that the only place in the basin where any extensive area of Cretaceous sediments might be preserved under the Tertiary cover is in the central and northern portion of the basin (see Plate 7). A study of the older rocks on the margin of the basin and of the structure of the Tertiary cover enables some conclusions to be drawn concerning the extent of the Cretaceous sediments.

The southwestern limit of the Cretaceous beds is probably the Murrayville Monocline. The Bungunna and Shaugh Bores, on the upthrow side of the monocline, both found Tertiary sediments on the pre-Mesozoic bedrock, while the Loxton Bore, very close to the monocline on the downthrow side, penetrated Cretaceous sediments. The Cretaceous sediments may either have been deposited against an escarpment on the site of the monocline, in which case they will thin out at the monocline, or else subsequent movement along the line might have preceded the removal of Cretaceous sediments from the upthrow side, in which case there may be a thick Cretaceous section on the downthrow side of the monocline. The cuttings and meagre core recovered from the bottom few feet of the Loxton Bore were interpreted by the geologists of the Australian Oil and Gas Company as indicating boulders of Kanmantoo rocks (metamorphosed Cambrian)

cf. p. 51
ref. to Devonian
on bedrock

in the sediment. Boulders have been reported by several people, notably Kenny (1934), within finer sediments at various horizons in the Rolling Downs Group and attributed to glacial action. This idea has been discredited, but the presence of the boulders seems to be proved, although the writer saw none in position. However until there is evidence to the contrary, it is better to take the boulders, if they are boulders, within the fine clays as proof of the immediate proximity of the unconformable contact with the pre-Cretaceous bedrock. Another explanation of the Karmantoo cuttings, and the difficulties in drilling, is that the borehole was drilled into the fault zone in the bedrock which must underlie the monocline and which probably dips to the northeast. What is known of the structure, and the closeness of the borehole to it, renders this explanation quite possible.

The southeastern margin of the Cretaceous beds is probably formed by a bedrock ridge on a continuation of the line of N.E.-S.W. ridges of steeply dipping Upper Devonian sandstones which can be seen at the margin of the basin. A continuation of the line of steeply dipping sandstones as far as the Murrayville Monocline has been deduced from the presence of a long, narrow, negative gravity anomaly. There is a remote possibility that the Cretaceous sediments might continue further to the southeast over this ridge into a second hollow which extends as far as the line of the Lachlan River. Borehole evidence shows that this hollow in the bedrock does exist. Also where this hollow in the bedrock reaches the edge of the basin southwest of Cobar there are some sediments which, it has been suggested, might be of Cretaceous age. However in the middle of the postulated area of Cretaceous beds, the Arumpo and Bidura Bores found below the Tertiary 'grey rock' in the former, and 'grey rock and soft blue slate' in the latter, which the government geologist dated as Palaeozoic. Therefore, although there may be some doubt about the identification of the cuttings samples, it is very probable that the Tertiary is underlain by Palaeozoic rocks in these bores and that if any Cretaceous sediments are present in this area they are in small thin patches.

The only evidence of the northwesterly limit of the Cretaceous beds is furnished by the Canopus No. 2 Bore, which penetrated the Tertiary cover and entered a white sandstone which Dr. Ludbrook, who studied cuttings, considers to be pre-Cretaceous. The absence of Cretaceous sediment in this borehole rules out the possibility of the Cretaceous basin extending to the northwest as far as the important line of faulting which forms the limit of the Tertiary basin and rules out therefore the possibility of a deep, faulted, northwestern boundary to the Cretaceous basin.

It seems very probable that the Cretaceous sediments in the Murray Basin are continuous with those of the Great Artesian Basin over the low part of the Broken Hill-Cobar ridge at Wilcannia. However the presence of numerous small outcrops of bedrock and the evidence from boreholes show that the ridge is still there at Wilcannia and that there is no question of an area of thick Cretaceous sediments linking up the two basins.

There is no direct evidence of the thickness of the Mesozoic beds in the middle of the Murray Basin except that from the Loxton and Company's bores which penetrated 251 feet and 209 feet respectively, without reaching the bottom in either case. However some help in estimating the greatest thickness which is possible can be derived from a study of the surrounding areas. In the main part of the Great Artesian Basin the structures are very gentle and sudden thickening of the sediments in a short distance is not known. It is probable therefore that the Cretaceous beds in

the Murray Basin will also have only the gentlest of folds and that there will be no very abrupt thickening. The greatest thickness will occur if there was rejuvenation in the Mesozoic along the zone of N.E.-S.W. structures between the Darling and Lachlan Rivers, as took place in the southern part of the Thallon Basin where the Mesozoic beds attain a thickness of 3,000 feet. The gravity survey shows that this N.E.-S.W. strike does continue as far as the Murrayville Monocline. On the other hand it is probable that the rejuvenation would not be so pronounced in the region of the Murray Basin as in the Thallon Basin which is much closer to the Mesozoic mobile belt of thick sedimentation in eastern Australia. Therefore it seems unlikely that the thickness of the Mesozoic beds in the Murray Basin will be greater than the 3,000 feet present in the southern part of the Thallon Basin. It might be considerably less.

Probably all or almost all of the Mesozoic beds will belong to the Rolling Downs Group which overlaps on to bedrock along most of the southwestern side of the Great Artesian Basin. Since in Aptian and Albian times the opening to the sea was to the northeast (Whitehouse, 1954), it is probable that the Rolling Downs sediments in the Murray Basin will be less marine in character than those in the Great Artesian Basin. This conclusion is supported by the fact that all the known Cretaceous beds in Victoria, on the southern side of the Murray Basin, are freshwater deposits. Highly porous sandstones of the Blythesdale Group may be present in the middle of the basin below the Rolling Downs clays and sandy clays. If the Mesozoic beds in the basin are thick, about 1,500 feet or more, there is a slight possibility that older beds, of the same age as the Jurassic Walloon Series, which are the lowest beds in the southern part of the Thallon Basin, will be present.

TERTIARY

At the beginning of the Tertiary era the roughly circular, saucer-like depression of the Murray Basin was formed and, although modified by subsequent earth movements, its outline has remained essentially the same to the present day. The sea invaded the basin from the south forming a shallow gulf in which there was intermittent deposition of marine and estuarine sediments ranging in age from Eocene to Pliocene and perhaps Pleistocene, and having a maximum thickness of 1,500-2,000 feet. Across the mouth of the gulf there was a ridge, the Padthaway Ridge, which separated the slowly subsiding Murray Basin on the north from the rapidly subsiding Gambier Sunklands to the south in which the sediments are much thicker. The Tertiary sediments in the basin are now almost entirely covered by a blanket of aeolian sand, river alluvium and concretionary limestone, usually referred to in South Australia as travertine. Apart from a few small patches around the edges, the only outcrops are in the steep cliffs along the lower part of the Murray River from Renmark down to the sea. A large amount of information has also been derived from the numerous water bores in the basin.

Most of the geological work which has been done has been related to the study of water supply and most of the information has come from boreholes. A good summary of what is known of the Victorian part of the basin was given by Gloe (1947). Prof. Howchin (1929) and more recently Prof. Hills (1939) have studied the physiography of the basin and its relation to structure. The greatest contribution to the stratigraphy of the Tertiary sediments was made recently by Dr. Ludbrook, palaeontologist of the South Australian Mines Department, who studied the samples from many of the water bores in South Australia, and, using this borehole information supplemented with some from outcrops, compiled a stratigraphic table correlating the formations mainly by their microfauna (Ludbrook, 1957).

The writer studied the outcrops in the cliffs along the banks of the Murray River between Renmark and Murray Bridge. Descriptions of several parts of the cliffs have been given previously by Howchin (1929) and Barnes (1951), but there has not been a study of the changes in lithology and thickness. Sections were measured at more than thirty places and rough estimates of elevations were made (Appendix I). This study, helped by information from boreholes, showed a series of monoclines in the Tertiary sediments, no doubt caused by faults in the bedrock, and the behaviour of the sediments over the monoclines proved that movements had taken place at several different periods. The only one of these monoclines which had been recognized previously was the largest, the Murrayville Monocline. In the compilation of the structural map of the Tertiary rocks (Plate 7) use was made of the measured sections, all published borehole information which could be found, and unpublished information on South Australian bores which Dr. Ludbrook was kind enough to provide. A palaeontological description of the samples collected was also made by Dr. Ludbrook. Fossil lists are not attached to this report but will be incorporated in the description of the Tertiary faunas which Dr. Ludbrook is preparing.

SEDIMENTS IN THE BASIN

Table 11 is the table of Tertiary sediments in the Murray Basin compiled by Dr. Ludbrook (1957). The details of the Eocene and Oligocene sediments refer to the area of the Gambier Sunklands and the flanks of the Padthaway Ridge which are included in the Murray Basin, sensu lato, by Dr. Ludbrook. The present report will concentrate on the sediments in the middle of the Murray Basin, where the Eocene beds consist of a series of sands and clays and the Oligocene and Miocene beds consist almost entirely of limestone. The sedimentary succession near the middle of the basin is known from several deep bores, notably the Loxton and Canopus No. 1 bores, the samples from which have been studied by Dr. Ludbrook.

Boreholes across the border in the Mallee region of Victoria encountered exactly the same lithological units and in spite of the scarcity of recent palaeontological information on the Victorian bores, a fairly obvious lithological correlation can be made over the short distance between the bores. The correlation is given in Table 12. The most recent summary of the stratigraphy of the Victorian part of the basin was by Gloe (1947) and this does not agree with Dr. Ludbrook's determinations of age. However Dr. Ludbrook's interpretation, which is based on detailed study of the microfauna and is helped by more recent work on the Tertiary faunas of other areas, is presumed to be the more accurate.

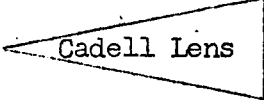

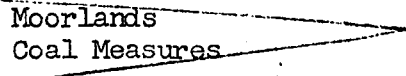
1. Lower Sands and Clays

The lowest Tertiary sediments throughout the whole of the basin, except the edges, are carbonaceous, silty sands, silts and black clays with some beds of clean porous sand. These beds do not crop out but are known only from boreholes. Carbonaceous material, lignite and pyrite are abundant in most of the beds. These sediments were deposited in an arm of the sea restricted in its communication with the ocean, no doubt by the Padthaway Ridge, and in the stagnant sulphurous waters of this gulf vegetable matter was incorporated in the sediments without being oxidised. There is no benthonic fauna; the only fossils which are found are foraminifera. These show the age to be Anglesean, a stage which is now included in the Eocene. The greatest known thickness of these beds is the 884 feet penetrated in the Company's Bore, and the greatest thickness will not be much more as this borehole is near the middle of the basin.

TABLE 11

TABLE OF TERTIARY FORMATIONS IN THE MURRAY BASIN

by N. H. Ludbrook (1957)

Series	Stage	Group	Formation
Pliocene	Kalimnan		Norwest Bend Formation
Upper Miocene	Cheltenhamian		Loxton Sands
	Unnamed		Bookpurnong Beds
Lower Miocene	?Bairnsdalian	Murray Group	Pata Limestone
	Batesfordian		Morgan Limestone 
			Finniss Clay
	Longfordian		Mannum Formation
Oligocene	Janjukian	Glenelg Group	Ettrick Marls 
			Naracoorte Member Gambier Limestone
			Compton Conglomerate
Upper Eocene	Unnamed	Buccleuch	C - Clay
	Unnamed	Group	B - Sands, limestone Buccleuch Beds A - Limestone, marl
Upper to Middle Eocene	Undifferentiated	Knight Group	Moorlands Coal Measures 
			Undifferentiated sands, gravels, clays and siltstones.

2. Ettrick Marls

The Ettrick marls were described first by Dr. Ludbrook from samples of bores in the southwestern corner of the basin and were not known at the surface till the writer found a small outcrop of 15 feet of the marls beside the Marne River which enters the Murray River from the west below Swan Reach. They are highly glauconitic/sandy marls with a maximum thickness of 100 feet. In the middle of the basin the marls pass into a facies of marly limestones and marls.

3. Mannum Formation

The Mannum Formation crops out in the cliffs along the banks of the Murray River from between Blanchetown and Swan Reach down to the mouth, and is the lowest Tertiary formation to crop out, except for a small outcrop of Ettrick marls in the valley of the Marne River. At the southerly end of the outcrop the formation can be seen at several places resting on granite and metamorphic Kanmantoo rocks, and at the upstream end of the outcrop it dips under the overlying Morgan Limestone. It is a yellow or cream coloured, rubbly limestone with an abundant fauna. Echinoids are especially abundant. Where the formation rests on bedrock near Mannum the lower beds are sandy, passing to limy sandstone in places, but further upstream the limestone contains only a little fine sand. In the Loxton bore the sediments of the same age consist of bryozoal limestones and marly limestones. In the Dimboola No. 1 bore, near the southern margin of the basin, the Mannum Formation is represented by marls and sands. To the east also the limestone passes into marls. The maximum thickness is of the order of 100 feet.

In many places on the Padthaway Ridge the Mannum Formation transgresses on to bedrock and, since the Eocene sediments were probably deposited over most of this area, it appears that there was a period of uplift and erosion before the deposition of the Mannum Formation in the region of the Padthaway Ridge, but not necessarily in the middle of the basin. The basal sands in some places contain rounded pellets of limonite which may have been derived from a layer of laterite which was being eroded at the time. In the road metal quarry on the banks of the Murray River opposite Mannum, the surface of the granite which is covered by the Mannum Formation is glossy and highly polished in a way suggestive of the action of marine currents or perhaps aeolian polishing.

4. Finniss Clay

Dr. Ludbrook describes the Finniss clay at the type locality at Mannum as 15 feet of poorly fossiliferous blue-grey, green and brown, marine clay resting disconformably on top of the Mannum Formation. This clay also appears to pass to limestone towards the middle of the basin.

5. Morgan Limestone

The Morgan Limestone forms the steep cliffs along the banks of the Murray River from about Blanchetown up to Overland Corner where, at the Murrayville Monocline, the limestone dips eastwards under the overlying Loxton Sands. It is a soft, cream coloured, highly porous limestone consisting mainly of organic remains, bryozoa being particularly abundant. It is a very pure limestone containing no sand and very little clay. A marly lens crops out south of Morgan, the Cadell marl lens of Dr. Ludbrook, consisting of blue-grey, very fine grained

marly limestone. There is another thin bed of marl at Waikerie and a third clay bed, consisting of 15 feet of highly gypseous clay, is present near the top of the limestone at Overland Corner. This fauna is considered to be typically Batesfordian, a stage which is thought to be Lower Miocene.

Towards the east and to the south the Morgan Limestone passes into marls and clays. The Dimboola No. 1 bore (Crespin, in Gloe, 1947) on the upthrown side of the Murrayville Monocline near the southern margin of the basin, found the Batesfordian stage represented by grey marls. The Arumpo bore northeast of Mildura penetrated only marls and clays without beds of limestone. The greatest thickness of the limestone seen at outcrop is slightly over 100 feet.

6. Pata Limestone

The Pata Limestone is a bed of porous, bryozoal limestone, up to 100 feet thick, which Dr. Ludbrook has defined entirely on the evidence of borehole samples from the area between Loxton and Pinnaroo, on the lower northeasterly side of the Murrayville monocline. It appears to follow the Morgan Limestone conformably. At the outcrops at Overland Corner the Loxton Sands rest on limestone which are probably part of the Morgan Limestone, although this has not been confirmed by palaeontological evidence. The limestone continues over the border into Victoria where it has not been differentiated from the Morgan Limestone.

The few boreholes studied by Dr. Ludbrook in the area show that the Pata Limestone wedges out eastwards approximately along the line of the Murrayville Monocline. Some of this thinning might be a depositional feature caused by contemporaneous movement along the monocline, but it is certain that the complete absence on the upthrown side of the monocline must be caused by erosion before the deposition of the Loxton Sands, as there must have been some deposition in the area of sea connecting the inner part of the basin with the ocean. The wedging out from a thickness of 100 feet shows that any contemporary movement combined with post-depositional movements must have been at least 100 feet.

7. Bookpurnong Beds

The Bookpurnong Beds were originally defined from borehole material by Dr. Ludbrook, who described them as 'red-green and green micaceous marls up to 100 feet thick'. Later the writer studied an outcrop of 12 feet of the beds just above water level in the Murray River west of Loxton at a place described originally by Howchin (1929). A rich and varied fauna was collected and was described by Dr. Ludbrook. The Bookpurnong Beds have almost exactly the same distribution as the Pata Limestone, wedging out at the Murrayville Monocline, but they overlap the Pata Limestone in the southern part of the monocline, a fact which suggests that there was uplift and some erosion of the Pata Limestone before the deposition of the Bookpurnong Beds. However it is evident that the greatest part of the uplift took place after the deposition of the Bookpurnong Beds, and resulted in both the Pata Limestone and Bookpurnong Beds being removed from the upthrown block on the southwestern side of the Murrayville Monocline.

The Bookpurnong Beds continue eastwards over the border into Victoria and there can be little doubt that the 'Kalimnan' clays are the same formation, because they have the same lithology - 'stiff marls and blue clays with shells, often glauconitic towards the base' - and because they have the same stratigraphical position above the limestones and below the fossiliferous sands.

Dr. Ludbrook considered the fauna to be a mixture of Miocene and Pliocene types and tentatively assigned to the beds a later Miocene age on the evidence of this mixed fauna, and because of the stratigraphic position between the Pata Limestone and the Loxton Sands, which were dated as Cheltenhamian, or uppermost Miocene. However Dr. O. Singleton, of Melbourne University, who examined the outcrop at Loxton some years ago considers that the fauna is definitely Cheltenhamian (personal communication). Since the Cheltenhamian is topmost Miocene this would mean that the Loxton Sands, which are separated from the Bookpurnong Beds by an angular unconformity, would almost certainly be of Pliocene age. This correlation is supported by the evidence of the Adelaide Basin, where sands similar to the Loxton Sands, resting unconformably on the under-lying Miocene, have been dated as Pliocene (Glaessner, 1953). It seems probable that the earth movements at the two places were contemporaneous, taking place at the end of the Miocene or the beginning of the Pliocene, and that the sands which were deposited subsequently are of Pliocene age.

8. Loxton Sands

The Loxton Sands have a wide distribution on the north-eastern side of the Murrayville Monocline and also, unlike the Pata Limestone and Bookpurnong Beds, they have a wide extent over an eroded surface of Mannum Formation and Morgan Limestone on the upthrown block on the southwest. The sands on either side of the monocline are of a different facies and it appears that there was an underwater escarpment on the site of the monocline during deposition. On the east side of the monocline the sands form intermittent cliffs giving good exposures from Moorook as far upstream as Renmark. The greatest thickness visited at one place is about 80 feet, but the Company's bore penetrated 105 feet. All the outcrops consist of a lower division, roughly half the total thickness, of fine sand and an upper of very coarse, gritty sand. At Moorook which is on the slope of the monocline the lower division consists of bright yellow, unconsolidated, fine micaceous sand with several thin, coarse layers with some associated streaks of fine clay which appear to be caused by some rhythm in sedimentation. Almost all of the fossils are restricted to the thin, coarse layers. These consist of thick-shelled lamellibranchs, oysters, and some echinoids. A short distance to the east the same soft, yellow micaceous sand crops out in cliffs along the banks of the river but no fossils were found. At least no megafossils were seen; an examination might reveal some foraminifera. The cliffs further upstream are composed of sands which, although of different lithology, being more coarse and containing less mica, might be of the same age, and if this is so it is possible that an unfossiliferous facies of the Loxton Sands might continue to crop out as far upstream as Renmark or even on the banks of the Darling River, before disappearing under sands of Quaternary age. The fossiliferous sands in the bores in the Mallee region of Victoria, which are usually called 'Werrikooian' in Victoria are probably of the same age as the Loxton Sands.

The Loxton Sands on the uplifted block on the southwestern side of the Murrayville Monocline differ in being thinner, coarser and much more firmly cemented. They consist of very coarse, strongly false bedded grit with shells scattered through it, resting on a stained and eroded surface of Morgan Limestone. The megafauna consists mainly of oysters and thick shelled types of lamellibranch, with some terebratuloid communities in the holes in the pitted surface of the underlying limestone. The degree of hardness varies, but on the whole the sands are much better cemented than those of the Moorook-Renmark area, and are used at Waikerie as a

building stone. The plane of unconformity is fairly level, but one buried channel 30 feet deep was seen in the cliffs four miles below Morgan. Barnes (1951) mentioned 300 feet of these sands at one place and, if these are all Loxton Sands, they might indicate the position of a deep channel eroded in the limestone before the deposition of the Loxton Sands. In the cliffs between Waikerie and Cadell the false bedding is very pronounced and is uniform in direction indicating deposition of the grits by currents flowing from the north and northeast.

Further downstream, below the hamlet of Purnong, there is another change of facies and return to a facies very similar to that at Moorook. At Purnong there is a monocline, which was named the Purnong Monocline, similar to the Murrayville Monocline, but having an east-northeasterly direction. On the south side of this the Loxton Sands thicken to 75 feet in a distance of $2\frac{1}{2}$ miles and consist of soft, yellow, micaceous, fine sand, as at Moorook, with some coarse shelly beds. It is of interest that a conglomerate bed in the sands contains small pebbles of ferruginous laterite derived from the erosion of a contemporary laterite layer.

In the earth movement preceding the deposition of the Loxton Sands the rocks along the lower part of the Murray Between Morgan and Mannum were tilted northwards and eroded with the result that southwards from about Swan Reach the Loxton Sands rest directly on the Mannum Formation. There appears to have been an escarpment, subject to sub-aerial erosion, along the line of the Murrayville Monocline, since exposures on the left bank of the river a short distance above Overland Corner show Loxton Sands filling a gully cut in the limestone on the monocline.

Clear evidence of the nature and amount of later movements which followed the deposition of the Loxton Sands is provided by wedging out of the sands at several monoclinal flexures similar to the Murrayville Monocline and, like it, probably formed over faults in the bedrock. In addition to the Murrayville Monocline and the Purnong Monocline, already mentioned, there are also monoclines at Cadell and ^{Moorook} ~~Moorook~~ and another N.E.-S.W. monocline a few miles below Purnong (see Plate 7). All these monoclines have Loxton Sands on the downthrow side wedging out over the monocline, and Northwest Bend Beds resting on Loxton Sands on the downthrow side transgressing on to Morgan Limestone and Mannum Formation on the upthrow side. The thickness of Loxton Sands present on the downthrow side gives a minimum for the movement during and after deposition of the sands. The amounts are, on the Murrayville Monocline, about 100 feet, and on the Cadell, Blanchetown and Purnong Monoclines, 20 feet, 45 feet and 75 feet respectively. Several similar but much smaller features were noted but are not shown on the map. The monocline which Barnes (1951) thought was present at Walker's Flat and illustrated in his publication, is in fact caused by recent slumping of the limestone cliffs under gravity.

Dr. Ludbrook found a fauna in the Loxton Sands which is a mixture of Miocene and Pliocene types and which she takes as indicating a Cheltenhamian (Upper Miocene) age. However, as has already been suggested, the Bookpurnong Beds are probably Cheltenhamian and the Loxton Sands probably Pliocene. The miocene microfossils may be derived. This means that the pre-Loxton Sands earth movements, which are the greatest to affect the basin since deposition began in the Eocene, took place after the Cheltenhamian, early in the Pliocene. In the Adelaide Basin sands of Pliocene age also rest with angular unconformity on the underlying Miocene beds. (Reynolds, 1953 and Glaessner, 1953).

9. Norwest Bend Beds

The Norwest Bend Beds are a thin formation, usually less than 20 feet thick, which rests on the Loxton Sands with angular unconformity. The usual lithology is that of an oyster bed consisting almost entirely of Ostrea sturtiana, with some O. hyotidoides with a sparse sandy matrix. In a few places, notably the type area at Norwest Bend, the formation is a limy, shelly, rather coarse sandstone containing numerous lamellibranchs. Dr. Ludbrook gives the age as Pliocene.

The Norwest Bend Beds have been recognised only on the upthrow side of the Murrayville Monocline, the most easterly outcrop being on the left bank of the Murray River on Jackson's Station, approximately in the middle of the monocline. It seems probable that sands of the same age were deposited to the east, but as they are unfossiliferous, they will be indistinguishable from the unfossiliferous Loxton Sands and perhaps Quaternary sands. It appears that the block on the west side of the monocline formed a rocky, current swept shoal on which the oysters thrived, while the deeper sandy bottom east of the Murrayville Monocline was an unsuitable environment.

The angular unconformity between the Norwest Bend Beds and the Loxton Sands can be clearly seen at the Cadell Monocline, where the Norwest Bend Beds rest on Loxton Sands on the downthrow side, and over the monocline transgress on to the Morgan Limestone, showing that the Loxton Beds were displaced along the monocline and the sediment from the upthrow side removed before the deposition of the Norwest Bend Beds. There was movement along the monocline again after deposition of the Norwest Bend Beds which causes the base of the formation to be 33 feet lower on the downthrow side than on the upthrow side. The same can be seen at the Murrayville Monocline where the outcrop of the oyster bed at Jackson's Station, on the monocline, is about 60 feet lower than on the upthrow side of the monocline, just below Overland Corner.

These considerable displacements of the Norwest Bend Beds must have had a strong effect on the topography and the course of the drainage, and the Norwest Bend Beds should not be regarded as having been deposited in an estuary following the present course of the Murray River, although it is possible that the main channel in the Pliocene might have coincided with the present course in places. The present course of the river is very new, a fact recognised by Prof. Howchin (1929).

10. Blanchetown Formation

The name Blanchetown Formation is proposed by the writer for a thin series of clays, silts and fine sands which overlies, apparently conformably, the Norwest Bend Beds in the outcrops on the banks of the Murray River. The outcrop further up the river which was seen is on top of the high cliffs on the right bank of the river immediately below Overland Corner, where the base of the formation is 153 feet above sea level, and the furthest downstream is between Swan Reach and Purnong. Throughout this area the lithology is constant and distinctive, and it is certain that these beds are not merely a facies of the Norwest Bend Beds. The thickness is usually about 20 feet or less, the greatest thickness seen being 30 feet two miles below Swan Reach. The formation is usually in two divisions of roughly equal thickness. The lower is a very dark greenish, fine grained clay in which the only fossils which were found were some small crustaceans. The upper consists of well bedded, pale coloured silts and fine sands, showing small scale current bedding, with some interbedded clay of the same type as in the lower division. One of the clay layers examined by Dr. Ludbrook contained the following

foraminifera, 'mostly Elphidium cf. simplex Cushman with single specimens of Lagenonodosaria sp. and Cibicides sp., indicating deposition in shallow sheltered or brackish water' (Ludbrook, unpublished report).

The contact of the formation with the underlying Nor-west Bend Beds was not well enough exposed at any place to show if there were any signs of unconformity, but it appears that even if there was a break in deposition, there was no obvious angular unconformity. Most or all of the movements which displace the Nor-west Bend Beds seem to have displaced the Blanchetown Formation. For example it thins from about 30 feet to 13 feet across a monocline visible in the cliffs at Swan Reach. The fossils in the formation do not provide conclusive evidence of age and either a Pliocene or a Pleistocene age is possible. Greenish clays very similar in lithology and stratigraphic relationships, which crop out on the coast south of Adelaide, have been tentatively assigned to the Pleistocene mainly because they rest unconformably on a weathered surface of Pliocene beds (Reynolds, 1953 and Campana and Wilson, 1954). On the evidence available at present a choice cannot be made between a Pliocene and a Pleistocene age for the Blanchetown Formation.

MARGIN OF THE BASIN

On all sides of the Murray Basin peneplains rise from beneath the Tertiary sediments, fairly gradually in most places but dislocated by faulting in some, to form an elevated rim to the basin. The rim is lowest on the northern side where the plains of the Murray Basin merge into those of the Great Artesian Basin with only a slight intervening uplift along the Broken-Hill-Cobar ridge. On the west, a faulted erosion surface, with some patches of Tertiary sediment remaining on it, has been uplifted to heights of up to 2,000 feet to form the Mount Lofty Ranges, which separate the Murray Basin from Gulf St. Vincent. On the eastern and southern sides of the basin the erosion surfaces have been elevated to heights of more than 6,000 feet forming the Dividing Range, an uplifted belt following the margin of the continent and separating the inland basins from the ocean. The well preserved erosion surfaces at various levels in these young mountains provide excellent evidence of the successive cycles of uplift and erosion in the Tertiary, which have not yet been the object of detailed study and interpretation. However the salient features can be distinguished.

The highest surface is in eastern Victoria where there are flat topped residuals, as at Bogong High Plains and Dargo High Plains, at elevations of 6,000 feet. These uplifted plateaux are deeply dissected. Westwards the Dividing Range becomes lower and less deeply dissected until around Casterton, near the South Australian border, it is no more than a low arch in an immature state of dissection. The Padthaway Ridge can be regarded as a low prolongation of the east-west line of uplift which formed the Dividing Range in Victoria.

On the areas of Tertiary uplift on the southern and eastern sides of the Murray Basin there were extensive spreads of volcanic rocks, almost entirely basaltic with very small amounts of acidic types, extending as far west as the southeastern corner of South Australia. They are in two main series, the Older Volcanics and the Newer Volcanics. Under the sheets of basalt are patches of gravels, usually filling buried stream channels, - the 'deep leads' of the gold miners - which correspond in age with the volcanics and are usually referred to as the Older Deposits and the Newer Deposits. The Older Volcanics are restricted in distribution to the eastern half of Victoria and New South Wales where they form cappings on the highest residuals of the erosion surface, and on the south side of the Dividing Range, are interbedded

with Anglesean (Eocene) sediments in the Gippsland Basin. It appears that most of the Older Volcanics were extruded in Eocene times, but the continuation of volcanic activity into the Miocene is shown by an outcrop west of Melbourne where basalts of the Older Volcanics are interbedded between the sediments of Janjukian age and sediments of Balcombian age. The Newer Volcanics were extruded only on the lower part of the Dividing Range in western Victoria. They range in age from Pliocene to Recent.

In general the two main periods of volcanic activity can be seen to be related in space and time to the two main periods of uplift. The extrusion of the Older Volcanics was related to the earlier period of uplift in eastern Victoria and the extrusion of the Newer Volcanics to the later uplift in western Victoria. Although there was further extensive uplift in the late Tertiary in eastern Victoria there was no extrusion of basalt. Thus it appears that the extrusion is related to the early period of uplift.

Vast areas of the erosion surfaces are covered with rocks of varying composition - siliceous, kaolinitic or ferruginous - caused by deep chemical weathering, leaching and redeposition on a mature peneplain surface. These are the 'duricrusts' which Woolnough (1928) first defined in Australia. David (1950) considered that the formation of the duricrusts took place only in the Lower and Middle Miocene and therefore that the deformation of the duricrusted surface was caused entirely by earth movement later than Middle Miocene. Largely as a result of this evidence he deduced that almost all of the uplift of the dividing Range took place in the Pliocene 'Kosciusko Uplift'. It now appears probable, however, that the formation of the duricrust began much earlier. Limonite pellets in the basal sands of the Mannum Formation (Oligocene) appear to have been derived from the erosion of a contemporary laterite layer. Several old boreholes on the Victorian part of the Murray Basin were said to find 'pipeclay' below the Anglesean (Eocene) sediments. This 'pipeclay' is probably a kaolinitic residual deposit similar to those found on top of slates at the southern margin of the basin. It appears therefore that the formation of these residual deposits began on the peneplain surface, in some places at least, as far back as the Eocene, and that their presence cannot be taken as proof that the uplift of an erosion surface was all later than Middle Miocene.

STRUCTURE

The dominant type of deformation in the Tertiary was a sinking of the Murray Basin accompanied by an uplift of the Dividing Range along the margin of the continent, with faulting subordinate in importance to gentle warping. The downward movement of the basin was not uniform but was interrupted by numerous small uplifts. The basin was cut by faults into blocks and in these periods of uplift there was differential movement between the blocks and slight tilting, the amount of which can be deduced from a study of the sediments which are bent to form monoclinial flexures over the faults in the bedrock.

The faults have a uniform pattern. In the eastern part of the basin the Echuca and Lake Tyrrell faults have a direction slightly east of north and in the western part the Murrayville, Cadell and Murbko monoclines have a N.W.-S.E. direction. All these faults and monoclines have the downthrow side on the east and separate faulted blocks which have a gentle tilt to the west or southwest. The displacement along the Echuca and Lake Tyrrell Faults has been small and recent and has been recognised only by its effect on the

physiography. The displacements in the western part of the basin have been greater. It is interesting to note that the series of en echelon faults in the Adelaide region, on the western side of the Mount Lofty Ranges, have a N.E.-S.W. direction and downthrow to the north, presenting a mirror image of the tilted blocks in the Murray Basin. The eastern and northwestern boundaries of the Murray Basin are fault controlled, coinciding with large fault lines in the Precambrian and Palaeozoic rocks, but there seems to have been relatively little Tertiary movement along the western boundary fault and almost none along the northwestern boundary fault (the Redan Fault). This must be because the Tertiary stress pattern did not favour movement on faults in this direction.

The form of the monoclines in the Tertiary sediments is variable, depending on the amount of movement along the bedrock fault and the thickness of Tertiary sediment. An example of a monocline near bedrock is provided by the N.W.-S.E. monocline with downthrow to the northeast between Purnong and Mannum. The bedding at the top of the Mannum Formation, which is only 50 feet above bedrock on the upthrow side, changes in level 48 feet in a horizontal distance of 100 yards and the greatest dip over the monocline is 13° . In contrast the greatest dip observed on a clay bed in the Morgan Limestone on the Murrayville Monocline in the Overland Corner outcrops was $1^{\circ}15'$ and the width of the flexure is shown on a section, based on borehole information in the Mallee Region of Victoria, as about 6 miles (Gloe, 1947). In this area the top of the Miocene Limestone is approximately 1,500 feet above bedrock on the downthrow side.

Tectonic History

The evidence from the sediments in the basin, augmented by some evidence from the margin of the basin, shows that there were four main periods of tectonic movement.

1. Early Eocene. The sinking of the Murray Basin, which caused it to be flooded by the sea, was accompanied by uplift of the margins resulting in the supply of sandy sediments to the Murray Basin and the deposition of a thick series of coarse sands in the Gambier Sunkland.
2. After deposition of the Bookpurnong Beds and before deposition of the Loxton Sands, that is at the end of the Miocene or, more probably, at the beginning of the Pliocene, Uplift of the basin resulted in the sea being driven out. Uplift along the Padthaway Ridge caused the sediments on the northern flank of the ridge to be tilted northwards. Erosion planed off the beds and removed all Miocene sediments from the Gambier Sunklands. There was a displacement along the Murrayville Monocline of at least 200 feet.
3. After the deposition of the Loxton Sands and before the deposition of the Norwest Bend Beds, that is in the Pliocene, but palaeontological work has not yet defined the age precisely, The basin was again uplifted and the sea again driven out. There was movement along several bedrock faults and the faulted blocks were tilted to the southwest. Planing off by erosion removed the Loxton Sands from the higher parts of the blocks. There was displacement along the Murrayville Monocline of at least 100 feet.

4. After the deposition of the Norwest Bend Beds and the Blanchetown Formation, the basin was uplifted and the sea driven out for the last time. There was further movement along the monoclines. The block on the southwestern side of the Murrayville Monocline was raised to form the present topographically high area and the Murray River cut the present steep gorge through the rising block. Physiographic evidence suggests that this last uplift did not take place long ago, and a Pleistocene age is perhaps more likely than a Pliocene age.

It is apparent that the two main periods of volcanic activity on the margin of the basin coincided with two main periods of faulting within the basin, namely Eocene and Pliocene.

QUATERNARY

In the Quaternary era, much of the surface of the Murray Basin was covered by a blanket of aeolian sand, usually in long straight dunes with an east-west to E.N.E.-W.S.W. direction parallel to the prevailing wind direction.

Some of the uplift of the block on the southwestern side of the Murrayville Monocline was Quaternary, producing a topographic 'high' on the structural 'high' through which the Murray River cut a narrow, steep gorge with walls 100 feet high. To the east of this barrier the larger rivers, the Murray, Murrumbidgee, Lachlan and Darling meandered over broad flood plains and deposited large spreads of grey and black silty clay and sand. Small movements along fault lines had a strong effect on the courses of these alluviating rivers and most of the major changes in direction of the rivers are found to coincide with fault lines.

In the western half of Victoria and the southeastern corner of South Australia the Tertiary volcanic activity continued into the Quaternary and many of the basalt flows and explosion craters are probably Recent.

J. SPENCE

MELBOURNE,

July, 1958.

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APPENDIX ISECTIONS MEASURED ALONG THE BANKS OF THE
MURRAY RIVER BETWEEN RENMARK AND MANNUM

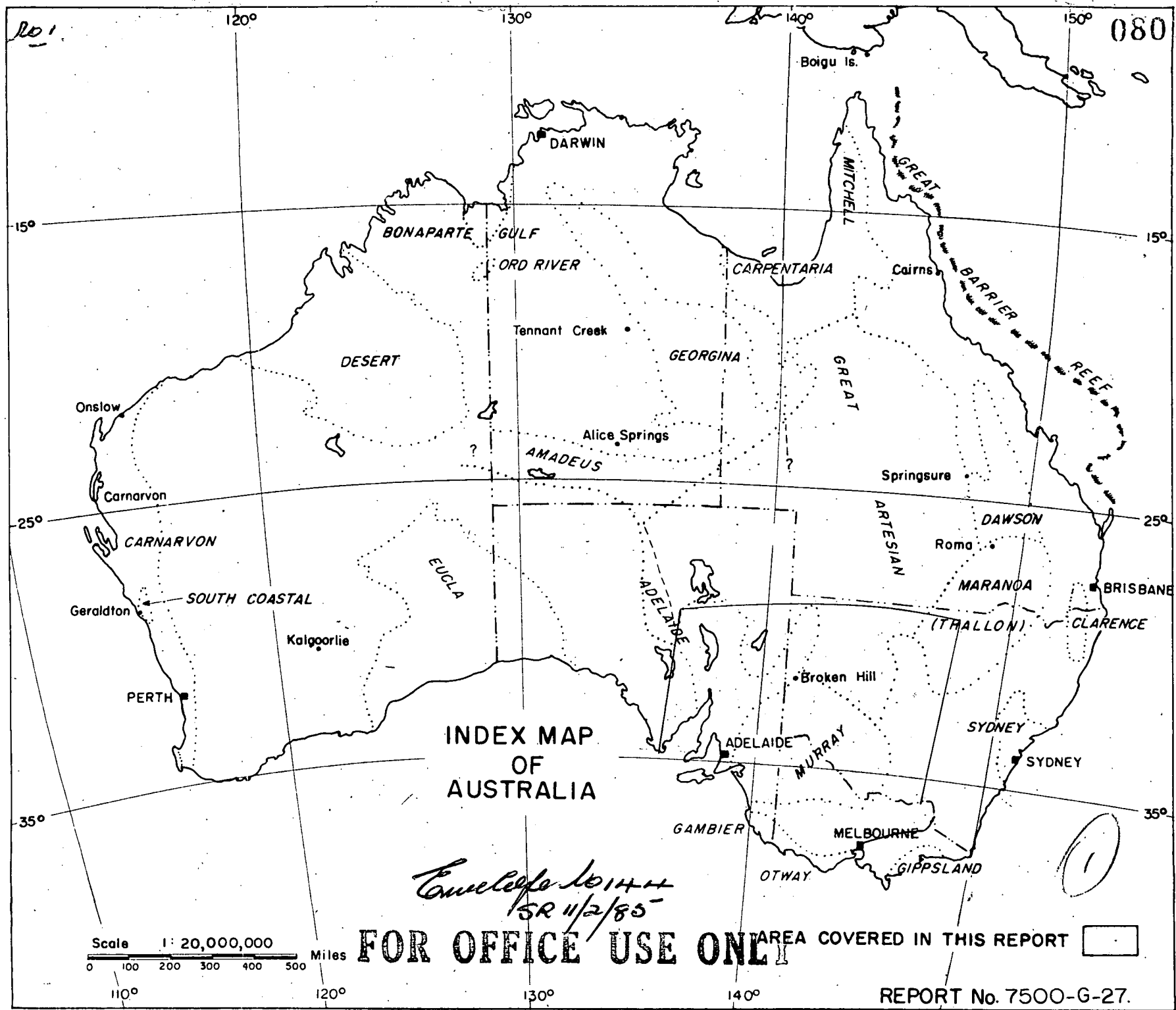
Thickness in sections marked thus * were not measured, but were estimated roughly by eye.

Levels were calculated by measuring the height above the water level of the River Murray and then estimating the river level at that point on that day from the levels at gauging stations and the gradient of the river.

Levels are in feet above mean sea level.

SECTION	LOCALITY	FORMATION	THICKNESS (in feet)	ELEVATION OF TOP
1*	21 miles above Loxton 1	Travertine	4	123
	15	? Loxton Sands	56	119
2*	15 miles above Loxton 2	Aeolian sand	30	131
	6	Travertine	10	101
		? Loxton Sands	30	91 191
3	Pyap Bend, west of Loxton 3	Travertine and aeolian sand	17	153
		Loxton Sands		
		Coarse sand	35	136
		Fine sand	47	101 201
		Bookpurnong Beds	12	54
4*	Moorook 4	Grit	5	
		Gap	10	
		Loxton Sands	20	
5*	1 mile west of Moorook 5	Travertine	4	101
		Red sandy clay	6	
		Loxton Sands		
		Grit	4	91 186
		Fine sand	40	
6	Jackson's Station 6	Red sandy soil and travertine	10	104
		Norwest Bend Fm.	4	94
		Loxton Sands		
		Coarse sand	8	82
		Fine sand	27	55
7*	East of Overland Corner Hotel 7	Travertine	5	102
		Red clayey sand	5	97
		Loxton Sands		
		Coarse sand	15	92
		Fine sand	2	77
		Gap	10	75
		Morgan Limestone	20	65 7*
8	1 mile below Overland Corner, Right Bank 8	Blanchetown Fm.	12	153
		Norwest Bend Fm.	102	142 *
		Morgan Limestone		
9*	4 miles below Overland Corner, left bank 9	Travertine and aeolian sand		
		Norwest Bend Fm.		
		Morgan Limestone	ca 50	
10	6 miles east of Waikerie Left bank 10	Travertine	5	176
		Aeolian sand	15	171
		Norwest Bend Fm.	5	156 *
		Morgan Limestone	110	151
11	Waikerie (after Barnes) Left bank 11	Travertine and aeolian sand	50	175
		Loxton Sands	20	125
		Morgan Limestone		
		Marl	12	105 *
		Limestone	58	93
12	6 miles below Waikerie Left bank 12	Aeolian sand	2	124
		Travertine	2	122
		Aeolian sand	12	120
		Loxton sands		
		Coarse sand	12	108
		Coarse shelly grit	25	96
		Morgan Limestone	41	71

ION	LOCALITY	FORMATION	THICKNESS (in feet)	ELEVATION OF TOP
13	9 miles below Waikerie 13 Left bank	Travertine and aeolian sand Loxton Sands Morgan Limestone	34 12 42	117 83 71
14	Midway between Waikerie 14 and C-dell Left bank	Travertine Blanchetown Fm. Norwest Bend Fm. Sands ? Norwest Bend Fm. Loxton Sands Morgan Limestone	5 9 10 5 15 43 30	120 115 106 96 91 76
21	6 miles above Blanchetown 21 Left bank	Norwest Bank Fm. Loxton Sands Morgan Limestone	13 9 91	144 131 122
22	1/2 mile above Blanchetown 16 22 Right bank	Travertine Norwest Bend Fm. Morgan Limestone	4 6 100	135 131 125
23	3 miles below Blanchetown 23 Left bank	Travertine Blanchetown Fm. Fine sand and clay Clay Limestone	7 6 6 85	139 122 116 110
24	8 miles below Blanchetown 24 Left bank	Travertine Blanchetown Fm. Limestone	9 12 76	119 112 100
25	1/2 mile above Swan Reach 25 Left bank	Travertine Blanchetown Fm. Norwest Bend Fm. Limestone ? Mannum Fm.	6 13 4 91	130 124 113 107
26	2 1/4 miles below Swan Reach 26 Left bank	Travertine Blanchetown Fm. Norwest Bend Beds Mannum Fm.	7 30 6 74	133 126 96 90
	6 1/4 miles below Swan Reach 27	Travertine Norwest Bend Fm. Mannum Fm.	6 12	
28	Marne River Right Bank of Murray River 28	Norwest Bend Fm. Mannum Fm. Ettrick Marl Marl Sandstone Karmantoo	18 ca 60 10 25	
29	Purnong Left bank 29	Travertine Mannum Fm.	5	
30	1/2 mile above Bowhill 24 30 Left bank	Travertine Loxton Sands Mannum Fm.	3 75	
31	4 miles due west of Bowhill 25 31 Left bank	Loxton Sands Mannum Fm.	30	
32	5 miles from Purnong 26 32 Right bank	Travertine Aeolian sand Loxton Sands Mannum Fm.		



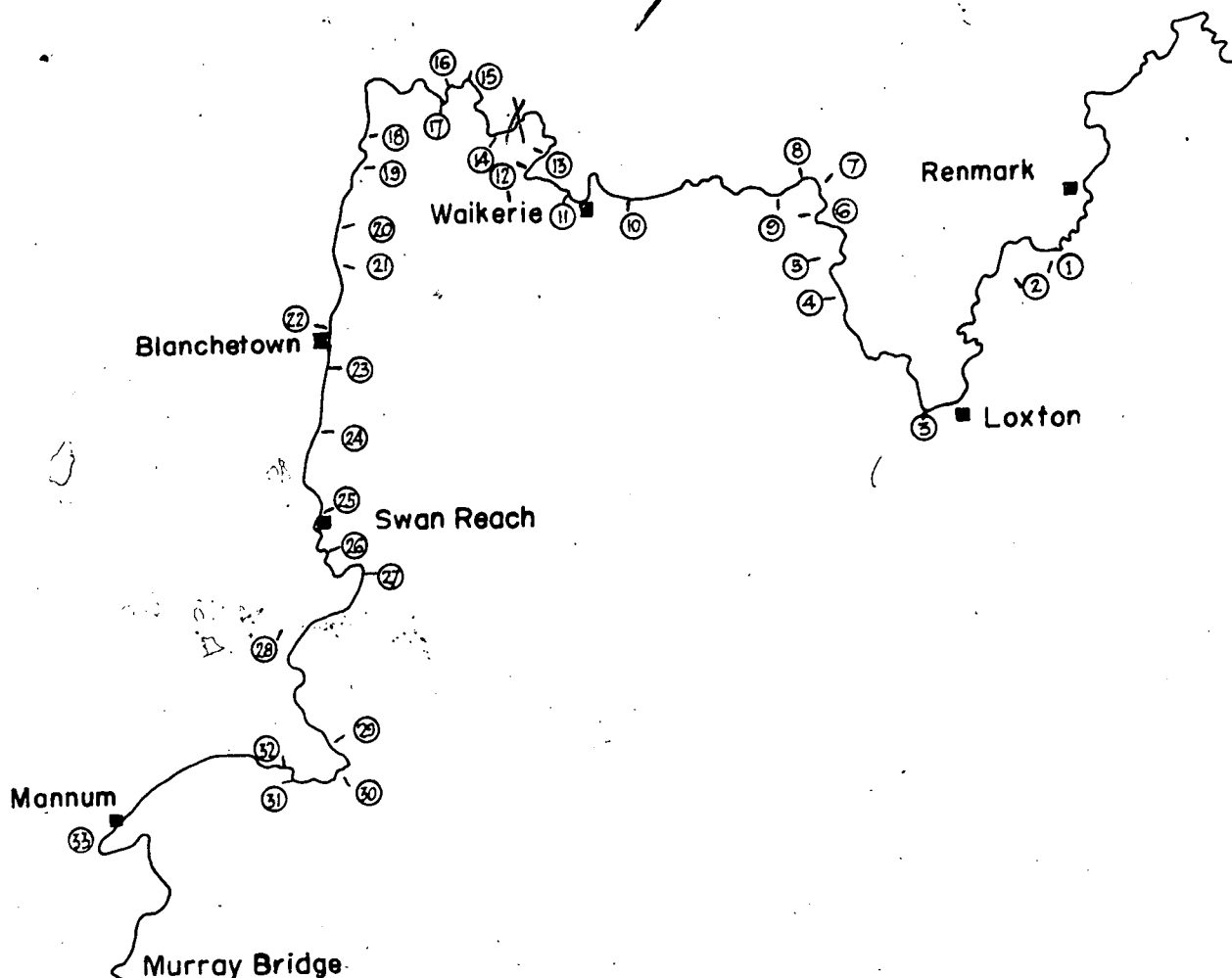
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MAP SHOWING THE POSITION OF SECTIONS
MEASURED ON THE BANKS OF THE
MURRAY RIVER

by J. SPENCE

SOUTH

AUSTRALIA

NEW SOUTH WALES

VICTORIA

SOUTHERN OCEAN

Pleistocene, Recent.
Tertiary, non-marine, Eyrrian Series.
Tertiary, marine.
Lower Cretaceous.
Jurassic and Lower Cretaceous (Victoria).
Triassic.
Permian.
Ravendale Beds.
Mulga Downs Beds and Mootwingee Beds.
Amphitheatre Beds.
Silurian-Lower Devonian (Victoria).
Silurian.
Ordovician.
Metamorphic rocks, mainly Ordovician (Victoria).
Cambrian.
Kangaroo Island Group.
Kammanoo Group.
Undifferentiated.
Marinon Series.
Sturtian Series.
Proterozoic.
Torrensian Series.
Willouran Series.
Katibity Series.
Archaean.

Q
T1
T2
K
JK
R
P
Dur
Du
Dua
SD
S
O
Om
Ck
C
Em
Es
Et
Ew
Pk
A

IGNEOUS ROCKS

Newer Volcanics. Pliocene to Recent.
Older Volcanics. Eocene to Oligocene.
Upper Devonian volcanics.
Lower and Middle Devonian volcanics.
Intrusive porphyries.
Upper Silurian to Lower Devonian.
Basic intrusive rocks.
Granite.

Tub
Tib
Duv
Div
Sp
G

Main faults.

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GEOLOGICAL MAP OF
THE MURRAY BASIN.

PLATE 1B
(WESTERN SECTION).

FROM REPORT: The Geology of the Murray Basin by J. Spence.

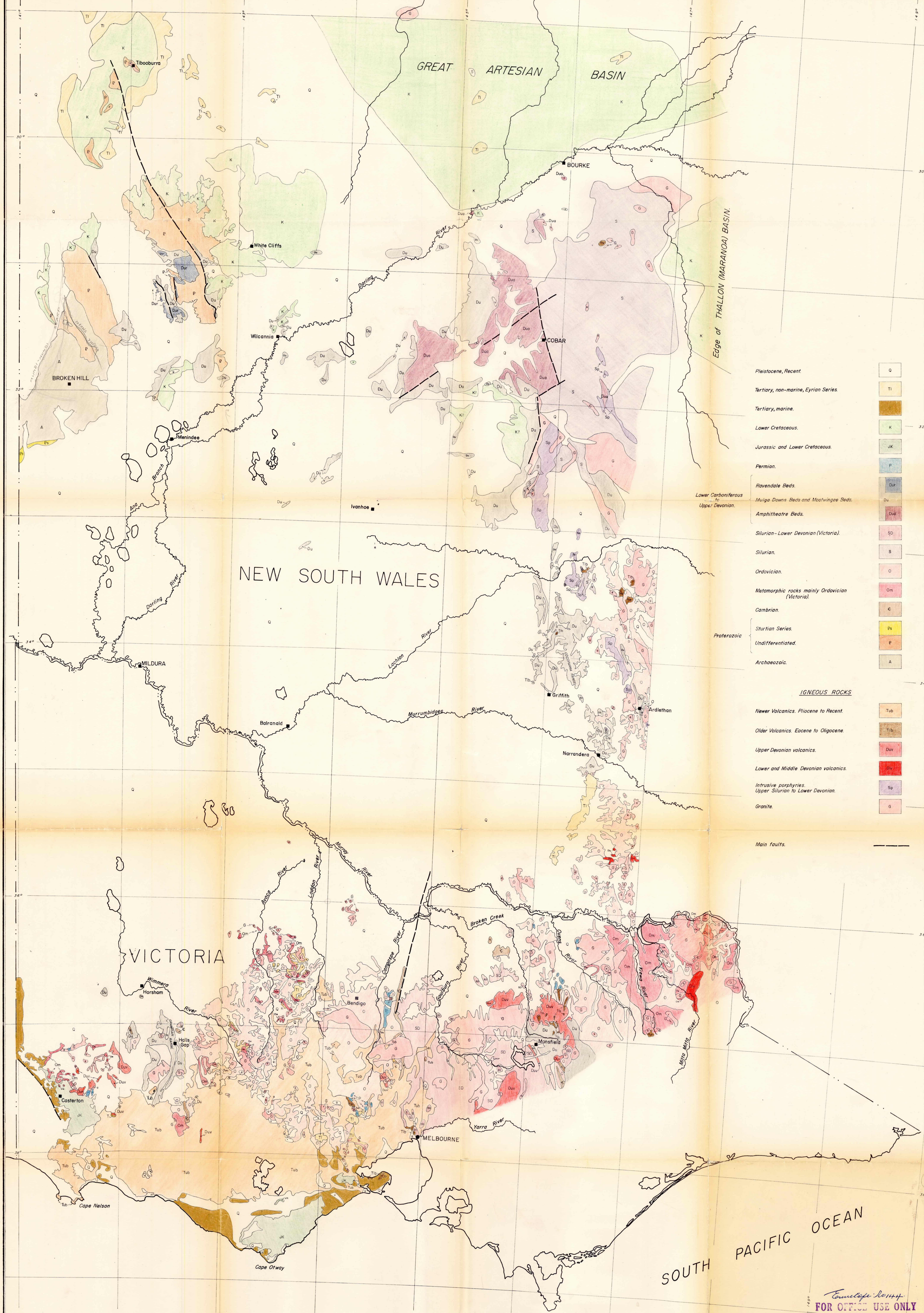
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- Pleistocene, Recent.* Q
- Tertiary, non-marine, Eyrian Series.* Ti
- Tertiary, marine.* K
- Lower Cretaceous.* JK
- Jurassic and Lower Cretaceous.* P
- Permian.* Dur
- Ravendale Beds.* Du
- Mulga Downs Beds and Moolingee Beds.* Du
- Amphitheatre Beds.* SD
- Silurian - Lower Devonian (Victoria).* S
- Silurian.* O
- Ordovician.* Om
- Metamorphic rocks, mainly Ordovician (Victoria).* C
- Cambrian.* Es
- Proterozoic.* P
- Undifferentiated.* A
- Archaean.* A
- IGNEOUS ROCKS**
- Newer Volcanics. Pliocene to Recent.* Tub
- Older Volcanics. Eocene to Oligocene.* Tib
- Upper Devonian volcanics.* Duv
- Lower and Middle Devonian volcanics.* Duv
- Intrusive porphyries. Upper Silurian to Lower Devonian.* Sp
- Granite.* G
- Main faults.*

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**GEOLOGICAL MAP OF
THE MURRAY BASIN.**

**PLATE 1A
(EASTERN SECTION).**

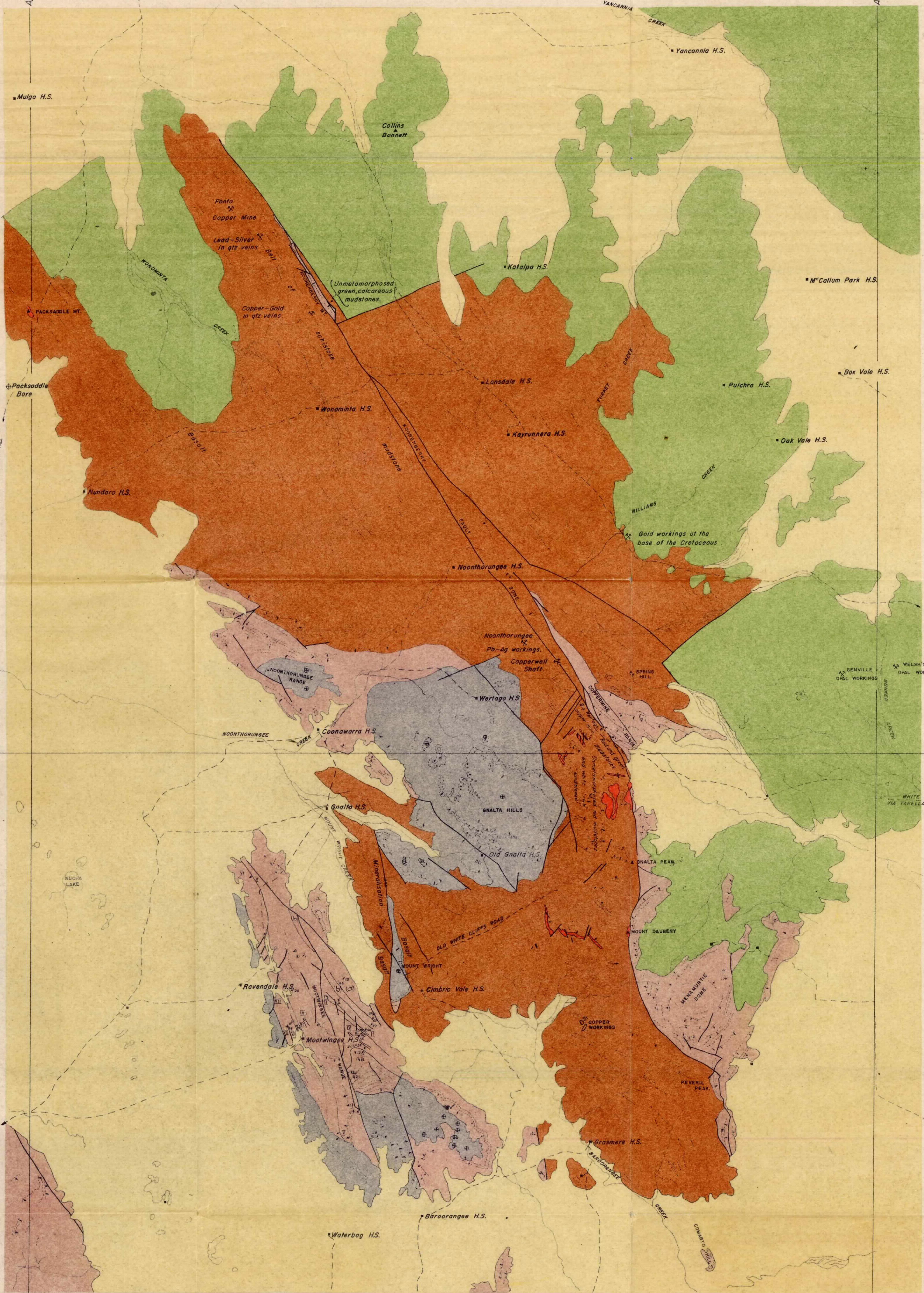
FROM REPORT: The Geology of the Murray Basin by J. Spence.

SCALE: 1 INCH = 10 MILES

Drafted: T. G. M. Cullough.
Checked:

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JULY 1958



LEGEND

- TERTIARY & QUATERNARY
- CRETACEOUS
- RAVENDALE BEDS
- MOOTWINGEE BEDS
- LINGULA BEDS
- PROTEROZOIC
- Acid igneous rocks in Proterozoic.

LOWER CARBONIFEROUS
UPPER DEVONIAN

- Fault.
- Geological boundary.
- Outcrop of bedding and direction of dip.
- Horizontal beds.
- Homestead.
- Road or track.
- Mine workings.

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**GEOLOGICAL MAP OF THE
MOOTWINGEE-KOONENBERRY AREA**

(MAP COMPILED FROM UNCONTROLLED PHOTOMAPS.)

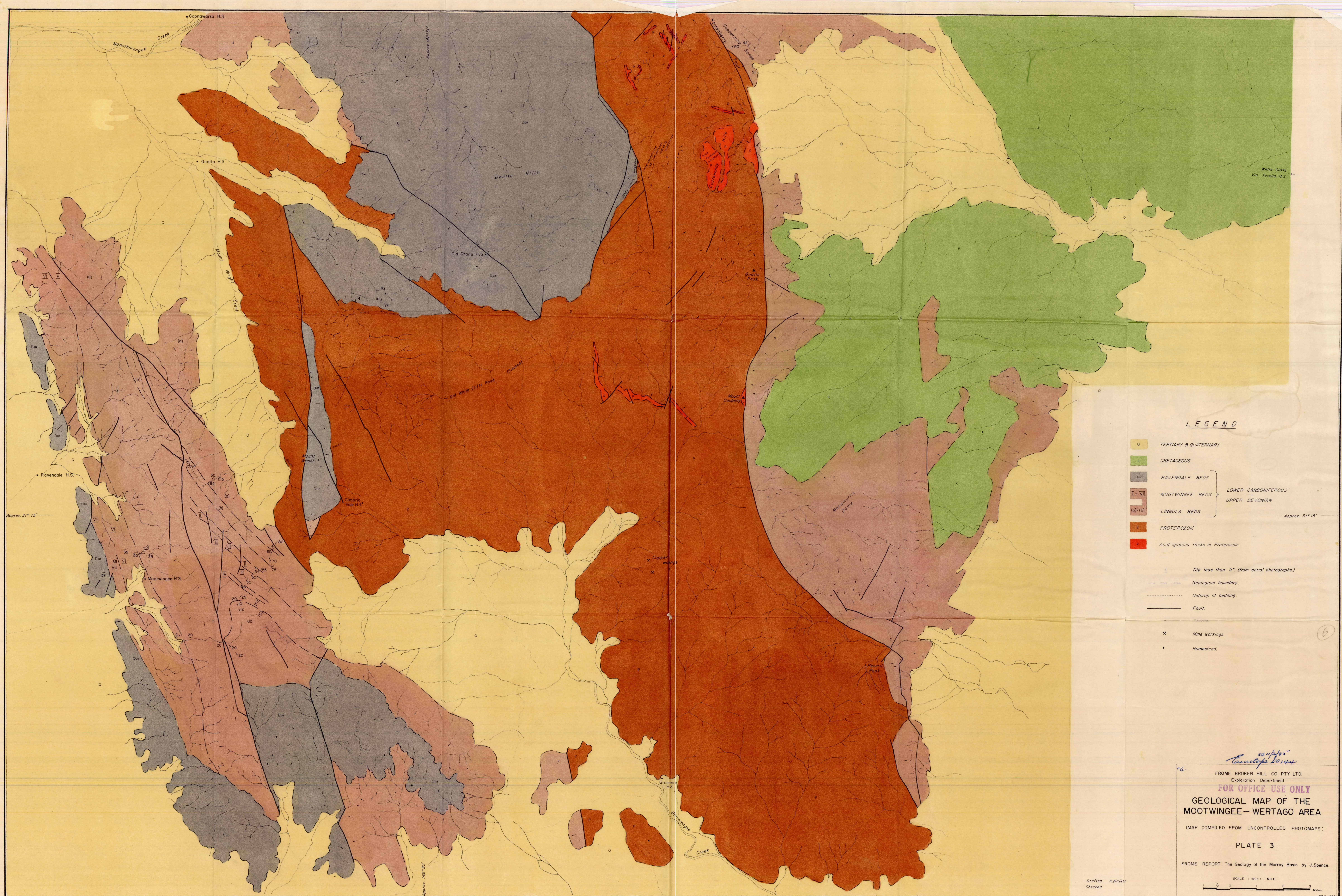
PLATE 2

FROM REPORT: The Geology of the Murray Basin. By J. Spence.

Drafted: R. Walker.
Checked:

SCALE: 1 INCH = 4 MILES
4 2 0 4 8 12 Miles.

JULY 1958



LEGEND

- Q TERTIARY & QUATERNARY
- K CRETACEOUS
- Dur RAVENDALE BEDS
- I-VII MOOTWINGEE BEDS
- (a)-(b) LINGULA BEDS
- P PROTEROZOIC
- Acid igneous rocks in Proterozoic.

- Dip less than 5° (from aerial photographs)
- Geological boundary
- Outcrop of bedding
- Fault
- Mine workings
- Homestead

20/1/50
Completed 20/1/50

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Exploration Department

FOR OFFICE USE ONLY

GEOLOGICAL MAP OF THE
MOOTWINGEE-WERTAGO AREA

(MAP COMPILED FROM UNCONTROLLED PHOTOMAPS.)

PLATE 3

FROM REPORT: The Geology of the Murray Basin by J. Spence.

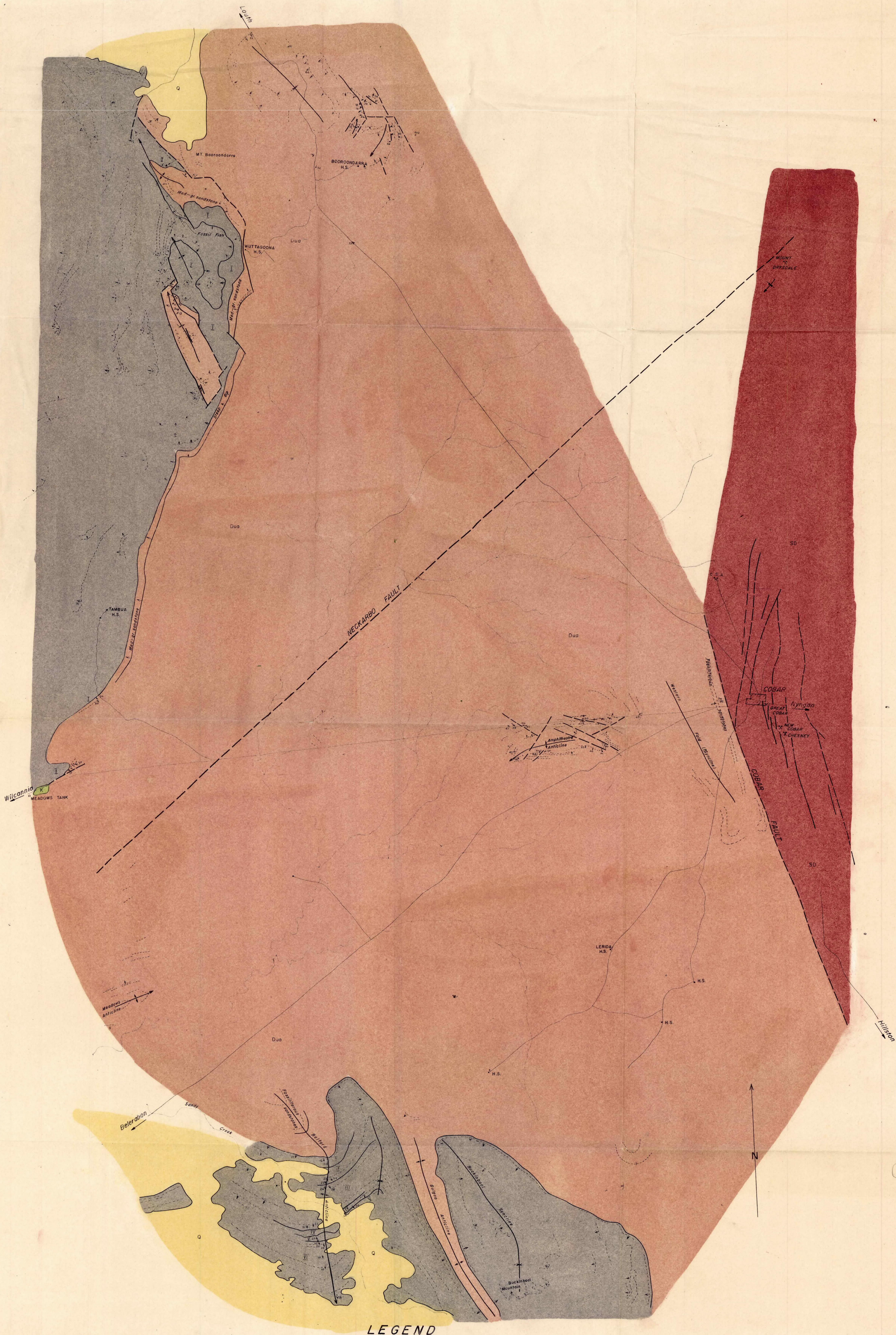
SCALE 1 INCH = 1 MILE

Drafted R. Walker
Checked

JULY 1958

ENU 144-5

7500-G-27



LEGEND

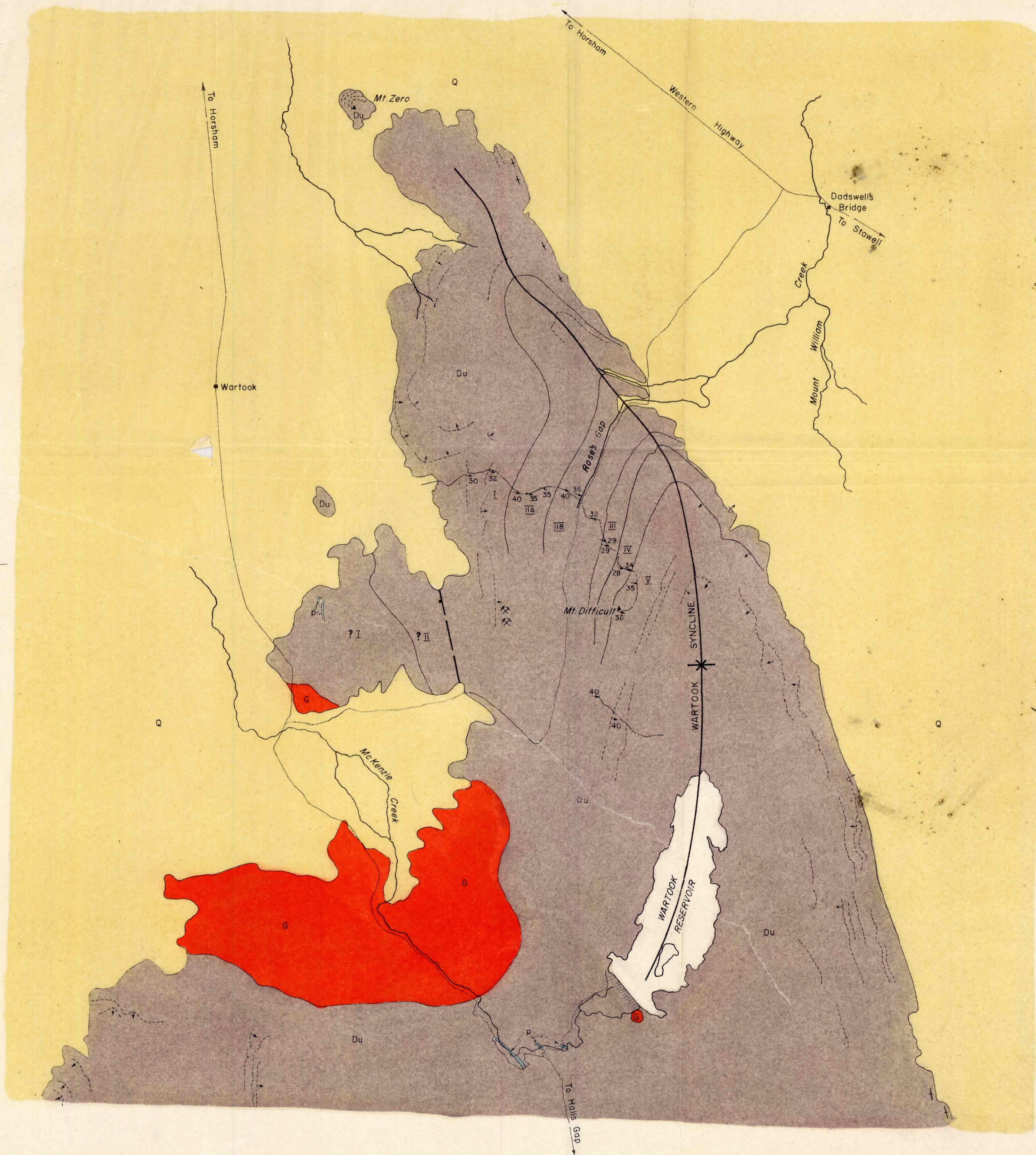
- Q QUATERNARY
- K CRETACEOUS
- VI BELFORD BEDS
- I-MULGA DOWNS BEDS
- Dua AMPHITHEATRE BEDS
- SD SILURIAN - ? L. DEVONIAN

LOWER CARBONIFEROUS
UPPER DEVONIAN

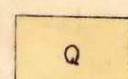
- Geological boundary.
- Outcrop of bedding and direction of dip.
- Vertical beds.
- Fault indicating downthrow.
- Fault, position uncertain indicating downthrow.
- Anticline.
- Syncline.
- Mine shafts and open cuts.
- H.S. Homesteads.
- Roads.

Note: - Large areas of the Amphitheatre Beds are covered with alluvial and residual deposits which are not shown.

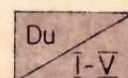
Envelope No. 11111
No 7. FROME BROKEN HILL CO. PTY. LTD.
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GEOLOGICAL MAP OF THE
AREA WEST OF COBARR
(MAP COMPILED FROM UNCONTROLLED PHOTOMAPS.)
PLATE 4
FROME REPORT: The Geology of the Murray Basin by J. Spence.
SCALE: 1 INCH = 2 MILES
2 1 0 2 4 6 Miles.



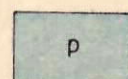
LEGEND



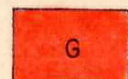
QUATERNARY



UPPER DEVONIAN—LOWER CARBONIFEROUS



PORPHYRITE



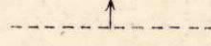
GRANODIORITE



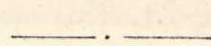
Fault (with indication of downthrow).



Geological boundary.



Outcrop of bedding and direction of dip.



Line of traverse.



Gold diggings.



Overturned strata.

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GEOLOGICAL MAP OF THE
NORTHERN END OF
THE GRAMPIAN RANGE, VICTORIA
(MAP COMPILED FROM UNCONTROLLED PHOTOMAPS.)

PLATE 5

FROM REPORT: The Geology of the Murray Basin. By J. Spence.

SCALE: 1 INCH = 1 MILE.

1 1/2 0 1 2 3 Miles.

JULY 1958

Drafted: R. Walker.
Checked:

ENU 144-7

7500-G-27



- Regions of thick sedimentation. More than 15,000 feet.
- Platform. Thickness less than 9,000 feet.
- Main faults.
- Anticline.
- Syncline.
- Boundary of Murray Basin.
- Measured sections at Mootwingee, Belford Anticline, Ardlethan-Cocoparra, Mansfield and Grampian Range respectively.
- Boreholes with U. Devonian - L. Carboniferous below the Tertiary.
- Boreholes with pre-Devonian below Tertiary.
- Negative gravity anomaly
- State boundaries.

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Exploration Department.
6/11/2/85

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STRUCTURAL MAP OF THE UPPER DEVONIAN-LOWER CARBONIFEROUS ROCKS OF S. EASTERN AUSTRALIA

PLATE 6

FROM REPORT: The geology of the Murray Basin by J. Spence.

Drafted: F.O. Barbaro
Checked: J. Spence.

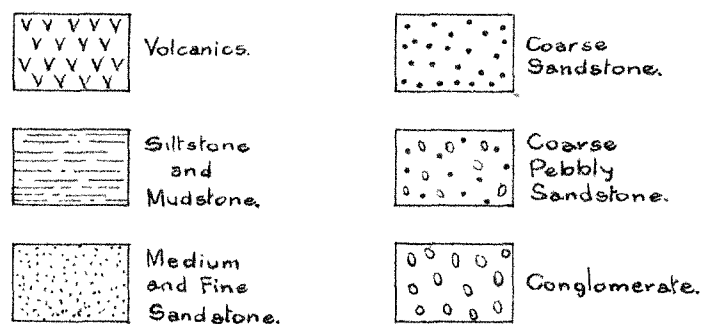
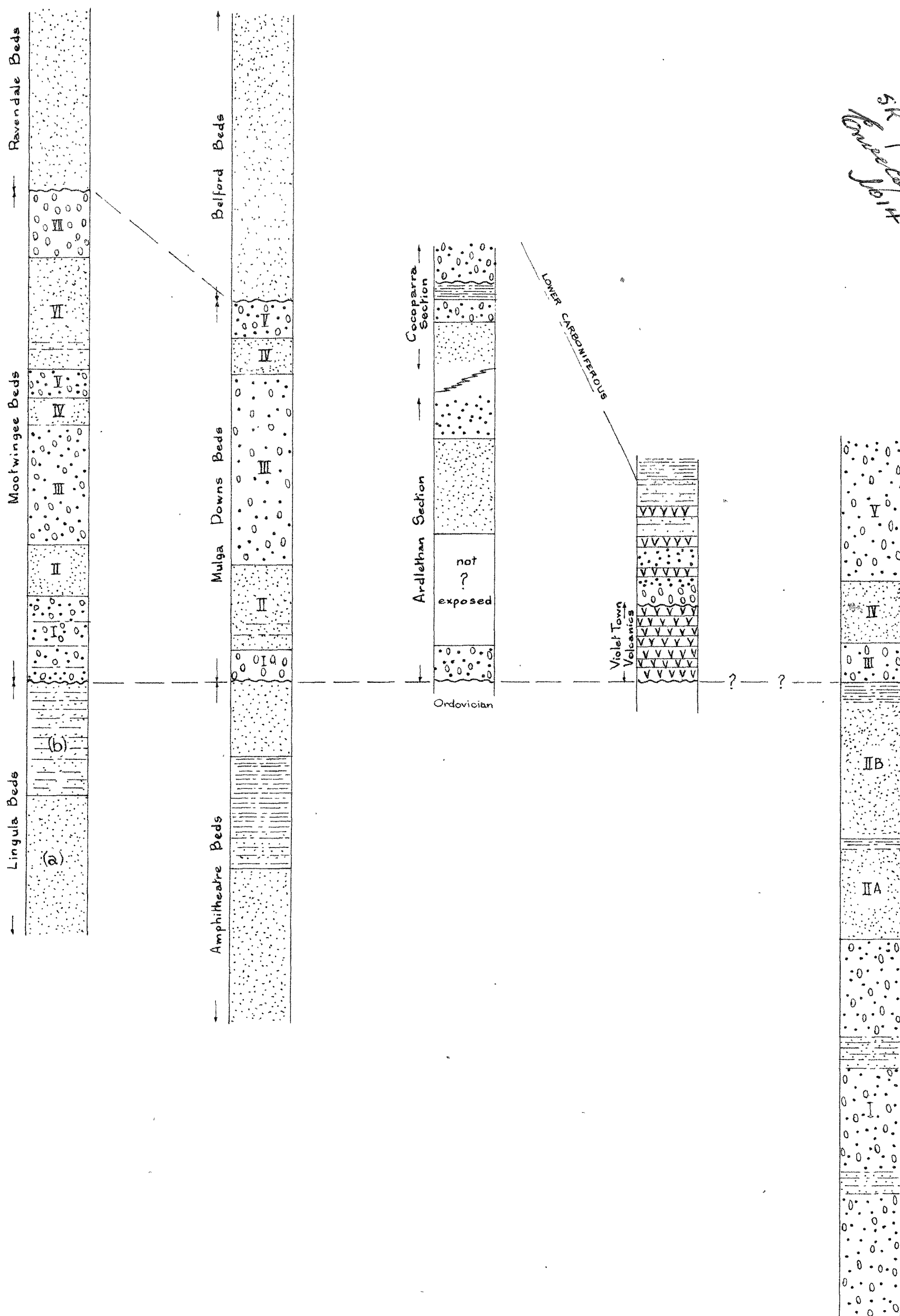
SCALE: 1 INCH = 4.8 MILES

48 24 0 48 96 144 MILES.

JULY 1956

MOOTWINGEE RANGE BELFORD ANTICLINE ARDLETHAN-COCOPARRA MANSFIELD (approximate) GRAMPIAN RANGE

5/11/2/8
H. R. 11/2/8
Cocoparra



Unconformity.

CORRELATION DIAGRAM
OF THE UPPER DEVONIAN-LOWER CARBONIFEROUS ROCKS
IN VICTORIA AND NEW SOUTH WALES.

FIG. 1

ENV 144-9